



CHRONIC ANKLE INSTABILITY:
UNDERLYING BIOMECHANICAL MECHANISMS
AND TREATMENT MODALITIES.

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General introduction

The foot and ankle complex can be considered the interface between the human body and the ground. It plays a crucial role in the functional performance of an individual during locomotion in all its forms, from daily living activities to the professional athlete. Therefore, the foot and ankle complex is subject to extremely high loads and, if these loads are not absorbed appropriately, it may become susceptible to a wide variety of injuries.¹¹⁸ Even Michelangelo's David - the famous statue located at the Galleria dell'Accademia in Florence - is not invulnerable as researchers have diagnosed David in 2014 with weak ankles putting him at risk of collapsing, paying the toll of 500 years of weight bearing.¹⁴

A systematic review, including data from 70 different sports in 38 countries with a total of 201.600 patients, revealed that the ankle joint is the second most frequently injured body site, after the knee joint, accounting for up to 20% of all injuries.³⁶ Of all these ankle injuries, the ankle sprain is the most commonly reported injury with a prevalence rate of 77%-85%.^{36, 96} In 85% of all ankle sprains, it entails a lateral ankle sprain.¹²⁷ Most of these ankle sprains occur during activities as jumping, landing, turning or running on unstable surfaces, referring to sports such as soccer, volleyball and basketball.³⁶ These injuries not only result in loss of participation¹¹², they also carry high socio-economic costs.¹²⁴

In many cases, an ankle sprain is considered your everyday injury which is easily treated with a good outcome. However, follow-up studies indicate the contrary. Many patients suffer from residual symptoms such as pain, swelling, weakness and subjective instability.^{71, 120} Three years after the initial ankle sprain, up to 25% of patients still experience pain and up to 34% report at least one resprain.¹²⁰ Furthermore, patients also report lower activity levels or even change to other sports as a consequence of their ankle sprain.^{1, 71} These residual symptoms have been termed chronic ankle instability (CAI). In the long run, CAI can even lead to articular degenerative pathologies such as osteoarthritis.^{51, 117} The focus of this introduction will be on the mechanisms and treatment of chronic ankle instability, as these are the subject of this dissertation.

Chronic ankle instability: the mechanism

Definitions

In literature, various definitions of CAI can be found. In general, most of these definitions have as key characteristics in their definition 'giving way' and 'repetitive ankle sprains' in common.¹⁹ A frequently used definition is the one by Hertel stating that 'CAI denotes the occurrence of repetitive bouts of lateral ankle instability resulting in numerous ankle sprains'.⁵⁴ It is only recently that Delahunt et al., based on available literature, attempted to suggest operational definitions to be used to describe this patient group.¹⁹ They described CAI as 'an encompassing term used to classify a subject with mechanical and functional instability of the ankle joint. To be classified as having CAI, residual symptoms ("giving way" and feelings of ankle joint instability) should be present for at least 1 year after the initial sprain'.¹⁹ Mechanical instability can be defined as 'joint range of motion beyond the normal expected physiological range of motion expected for that joint'.^{6, 8, 19, 24} Functional ankle instability refers to the situation whereby a subject reports experiencing frequent episodes of "giving way" of the ankle joint and feelings of ankle joint instability.¹⁹ Finally, "giving way" can be defined as 'the regular occurrence of uncontrolled and unpredictable episodes of excessive inversion of the rearfoot which do not result in an acute ankle sprain'.¹⁹

Models

About a decade ago, Hertel⁵⁵ proposed a universally accepted model representing mechanical and functional insufficiencies as contributors to the mechanism of CAI (fig. 1). This model attempts to give a comprehensive overview of the influencing factors and their interplay as they are not considered exclusive entities. When both mechanical and functional insufficiencies are present, recurrent ankle sprains may occur. Mechanical instability is thereby considered the result of anatomic changes, including either pathological laxity, arthrokinematic impairments, synovial or degenerative changes, or a combination of these alterations. Functional instability is believed to be caused by an impaired proprioception, neuromuscular control, strength and/or postural control.⁵⁵ These individual contributors will be explored further on in the introduction.

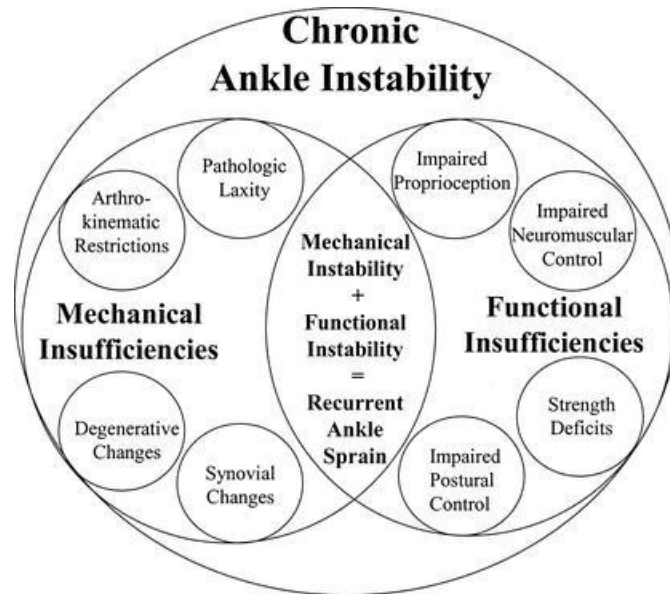


Figure 1. Hertel’s paradigm of mechanical and functional insufficiencies that contribute to chronic ankle instability (from Hertel J. *Functional Anatomy, Pathomechanics, and Pathophysiology of Lateral Ankle Instability*. *J Athl Train* 2002 Dec;37(4):364-7).

Hiller et al. recently suggested a potential evolution of the model of Hertel (fig 2).⁵⁷ Clinical experience illustrated that not all patients could be categorized in the current model. Some patients have both mechanical insufficiencies and perceived (functional) instability, but do not report recurrent ankle sprains. Other patients have perceived instability without mechanical instability and do suffer from recurrent ankle sprains, etc. Therefore, they introduced a model containing 7 different subgroups. These authors argue that heterogeneity of the spectrum of subjects with CAI may cause the diversity of results reported in studies on contributors to CAI.⁵⁷

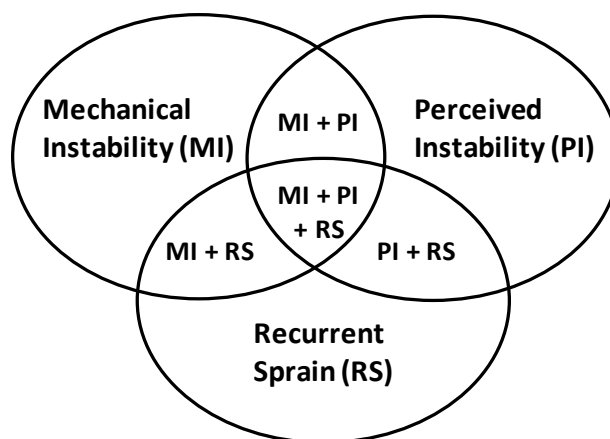


Figure 2. Hiller et al. Evolution of the model (adapted from Hiller CE, Kilbreath SL, Refshauge KM. *Chronic ankle instability: evolution of the model*. *J Athl Train* 2011 Mar;46(2):133-41).

Contributors

For the sake of clarity, so far it remains unclear which factors contribute to the mechanism of CAI. The controversy regarding possible contributors requires further elaborate research. There is consensus that there must be a multifactorial foundation to explain the development of CAI. Several potential contributors, some of them already mentioned, are being discussed in more detail.

Foot characteristics

Morphological variations of the foot and ankle complex could be associated with CAI. Concerning the calcaneus, a trend to increased varus alignment has been described in subjects with CAI.¹¹⁹ In addition to this increased varus angle, a higher medial arch has been observed in subjects with CAI compared to matched controls, representing a cavovarus foot type.⁷⁵ Furthermore, studies have shown a larger radius of the talus in subjects with CAI, indicating a flatter talus (based on a circle fitted to the talar surface at the talocrural joint in the sagittal plane), and smaller tibiotalar sector, as a measure for the tibial coverage of the talus.^{40, 80} These findings might reflect a decreased restraint of the talus in the tibia and therefore an unstable ankle configuration.⁴⁰ However, available evidence is limited and definitive conclusions might be premature. Morrison et al. indicated that more research is necessary to expand the knowledge on the relationship between foot characteristics and chronic ankle instability.⁹³ Insight into foot function might be enhanced by the use of multi-segmented foot models.⁹⁸

Pathological laxity

Sustaining an ankle sprain is associated with damage to the ligaments of the talocrural and subtalar joint. Based on the severity of this damage, ankle sprains can be classified.¹³⁵ The anterior talofibular ligament (ATFL) is the most easily injured followed by the calcaneofibular ligament (CFL). Incomplete healing of these ligaments might result in mechanical laxity.⁶³ Clinically, the integrity of the ATFL and CFL can be assessed using respectively the anterior drawer test and the talar tilt test. The diagnostic accuracy, however, of these clinical tests have been shown limited in subjects with CAI.^{15, 101} Furthermore, at this moment, the role of mechanical laxity in the mechanism of CAI is unclear as mechanical laxity is not considered a prerequisite for suffering from CAI.^{19, 44, 57}

Arthrokinematic alterations

Positional faults at the talocrural joint have been described to be associated with CAI. First of all, several studies have demonstrated a more anteriorly positioned talus with a reduced posterior glide in relation to the tibia, which might reduce the dorsiflexion range of motion (ROM) at the talocrural joint.^{25, 80, 130} This decreased dorsiflexion ROM might inhibit reaching a functional closed packed position of the ankle joint, which is believed to protect against accessory motion. Secondly, a more anteriorly positioned fibula has been observed at the distal tibiofibular joint.⁶² A hypothesis is that the anterior talofibular ligament is therefore less taut, resulting in more freedom of movement of the talus.⁵⁵ On the other hand, a more posteriorly positioned fibula in relation to the medial malleolus has also been described following an ankle sprain and in subjects with CAI, opening up the talocrural joint mortise.^{4, 33} If these alterations are present, the ankle joint might become more susceptible to an ankle sprain or episodes of 'giving way'.

Proprioception

The term proprioception describes all afferent information arising from internal peripheral areas of the body (fig 3) that contribute to postural control, joint stability, and several conscious sensations.¹⁰⁰ Freeman was the first to use the term "deafferentation" referring to a decreased afferent input as a consequence of damage to mechanoreceptors following an ankle sprain.³⁸ Currently, there is more focus on altered muscle spindle activity as an important afferent source explaining deficits in proprioception in subjects with CAI.^{68, 95} Impaired proprioception manifests itself by a disturbed joint position sense (active or passive), force sense and/or kinesthesia⁵⁶. This situation of disturbed afferent input might inhibit adequate reaction to external perturbation or result in a maladaptive positioning of the foot prior to touch down, possibly making the ankle susceptible for injury. Findings in literature, however, are inconsistent with some studies identifying proprioceptive deficits in subjects with CAI^{8, 72} while other studies found no differences compared to healthy controls.^{48, 105} A systematic review with meta-analysis concluded that there is little evidence supporting the association between an impaired joint position sense and CAI.⁵⁸ Various studies also failed to show a disturbed kinesthesia in subjects with CAI.^{64, 77} However, Doherty and Arnold did describe an impaired force sense in the evertor muscles in subjects with CAI.²⁷ In addition, Needle et al. demonstrated recently a diminished sensory traffic from muscle spindle afferents in the peroneal nerve at low levels of force, suggesting that early detection of joint loading may be compromised.⁹⁵

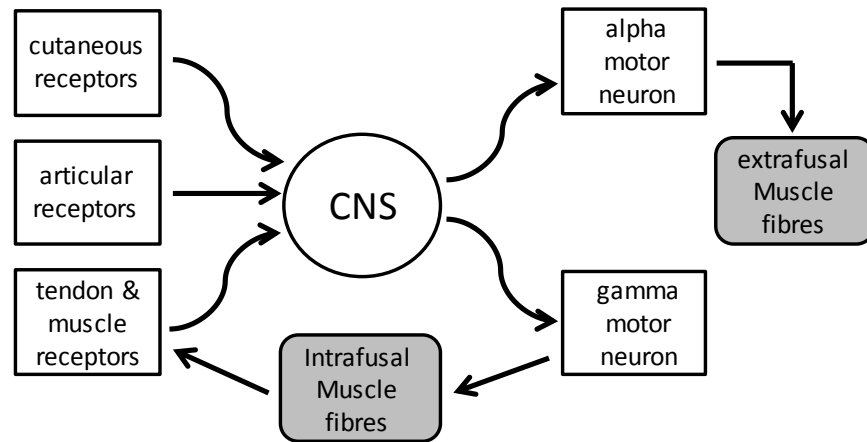


Figure 3. Hertel's paradigm of proprioception and neuromuscular control encompassing feedback and feedforward mechanisms. CNS=Central nervous system (adapted from Hertel J. *Functional Anatomy, Pathomechanics, and Pathophysiology of Lateral Ankle Instability*. J Athl Train 2002;37(4):364-375.).

Neuromuscular control

Neuromuscular control can be defined as the subconscious activation of dynamic restraints occurring in preparation for and in response to joint motion and loading for the purpose of maintaining and restoring functional joint stability.¹⁰⁰ Impairments in neuromuscular control can be due to alterations in the feedforward and/or feedback mechanism (fig 3).⁵⁶ As a measure for the feedback mechanism, muscle reaction time of the peroneus longus muscle to external perturbations has been extensively investigated in subjects with CAI. Although various studies have reported opposing results^{31, 32, 34, 60, 73, 79, 116}, a recent meta-analysis by Hoch and McKeon indicated that subjects with CAI do exhibit a delayed peroneal reaction time.⁵⁹ This feedback mechanism alone, however, cannot account for the susceptibility to ankle sprains. Konradson et al. found that the response time needed to actively evert the ankle joint after a simulated ankle sprain is too long to prevent damage to the lateral ligaments.⁷⁴ This implies an important role of the feedforward mechanism or the activation in preparation to joint loading. This anticipatory modulation of neuromuscular control is dependent on the alpha-gamma coactivation, regulating muscle preactivation which influences joint stiffness.⁴⁹ Additionally, residual arthrogenic muscle inhibition is believed to decrease the alpha motor pool excitability of muscles surrounding the damaged joint affecting the performance of the musculature.^{49, 56} This mechanism of arthrogenic muscle inhibition has been associated with CAI.^{87, 106} As the interaction between preparatory and reactive muscle activation patterns is important, any deficit in the feedforward and/or feedback mechanism might lead to an impaired neuromuscular control. Several studies evaluating neuromuscular control have shown e.g. a decreased m. peroneus longus activity both prior to and after ground contact in subjects with CAI during

gait, side cutting and various landing protocols.^{24, 104, 110, 111} Furthermore, neuromuscular deficits have been shown in the m. tibialis anterior, m. soleus, m. vastus medialis obliquus, m. rectus femoris, m. tensor fascia latae and the m. gluteus maximus in subjects with CAI during various tasks^{24, 115, 121, 129}. This impaired neuromuscular control might put subjects at risk of sustaining an ankle sprain.

Postural control

Postural control is defined as the capacity of a person to keep their center of mass over their base of support. The capacity to do this depends on the efficient integration of afferent visual, vestibular and somatosensory input to generate an adequate efferent neuromuscular response.¹³⁴ A deficit in any of these contributors may lead to loss of postural control.²⁶ Impaired postural control has been repeatedly demonstrated in subjects with CAI^{2, 99}, and is believed to be the result of a combination of deficits in proprioception and neuromuscular control.⁵⁵ Even bilateral deficits have been demonstrated in subjects with CAI indicating spinal or supraspinal motor control deficits⁵⁶. Research on CAI has investigated both static and dynamic outcome measures to evaluate postural control. Studies evaluating dynamic postural control, defined as maintaining balance while transitioning from a dynamic to a static state⁴², have been shown to be more consistent in identifying postural control deficits in subjects with CAI.⁸⁴ This is in agreement with other authors, suggesting that functional tasks may be more sensitive and specific in identifying subjects with CAI than static tasks.^{99, 102} Moreover, ankle sprains most frequently occur during activities that involve jumping, landing and cutting.³⁶ Various studies, evaluating ground reaction forces, have established the presence of dynamic postural control deficits in CAI.^{10, 102, 103, 131, 132}

Strength

The role of muscle strength in the mechanism of CAI remains ambiguous. Several studies have found diminished concentric and/or eccentric strength of the both the evetor and invertor muscles in subjects with CAI^{17, 52, 133}, whereas others did not^{5, 76}. In case deficits are present, the peroneal muscles might not have sufficient strength to counter the inversion moment associated with the ankle sprain mechanism.⁹⁴ Some studies also demonstrated a concentric invertor weakness.^{17, 52} Possible explanation could be an inhibitory reflex mechanism to these invertor muscles to avoid increasing tensile stress on damaged ligaments.⁵⁸ Several studies also demonstrated a decreased plantar flexion strength at the ankle joint to be associated with CAI.^{37, 46, 65} Additionally, strength deficits have been identified more proximally in the knee extensors and flexors⁴⁶, and hip abductors³⁹ in subjects with CAI indicating centrally mediated neuromuscular adaptations.

Biomechanics

Biomechanical research has indicated that joint kinematics are influential in the capability of modifying and controlling the high impact forces associated with landing tasks.¹³⁶ Inadequate control during landing tasks might possibly lead to injuries of ligaments and the muscle-tendon complex.³⁵ Research on kinematics in subjects with CAI revealed kinematic differences not only at the level of the ankle, but also of the more proximal joints, i.e. the knee and the hip compared to healthy controls.^{11, 23, 43} These adaptations might be inefficient to deal with the rapid and very high loading forces, possibly increasing the susceptibility to injury. Deviating kinematics are attributed to spinal and supraspinal adaptations to motor control.^{53, 56} The literature on these deviating kinematics in subjects with CAI, however, has not been consistent. Some studies have described a more inverted position of the foot during gait and landing tasks^{22, 24, 78, 91}, whereas others did not^{70, 92}. During running, subjects with CAI have demonstrated limited dorsiflexion ROM at the ankle joint.³⁰ In contrast, a greater ankle dorsiflexion prior to and post landing in a single leg jump has been demonstrated.¹¹ In addition, Brown et al. concluded that there is less foot clearance during terminal swing, which may increase the possibility of inadvertent foot contact.⁹ Notwithstanding some conflicting results possibly caused by difference in landing tasks, lower limb joint kinematics are considered a contributing factor in the underlying mechanism of CAI. However, further research is necessary to elucidate the possible influence of these biomechanical contributors.

Chronic ankle instability: rehabilitation

As a consequence of the assumption that CAI has a multifactorial foundation, rehabilitation should address the possibly various deficits present in patients with CAI. Therefore, an adequate screening of every individual patient is the keystone of an effective rehabilitation. Conventional treatment modalities are mostly focused at restoring ROM, increasing strength, restoring neuromuscular control and postural control²⁹.

Concerning ROM deficits, it is important to make a distinction between arthrokinematic and osteokinematic restrictions.²⁹ To treat arthrokinematic restrictions as discussed above, a posterior talar glide mobilization can be performed.^{81, 125} This mobilization technique can be executed alone or in combination with a dorsiflexion mobilization, i.e. osteokinematic approach.^{81, 125} In addition, osteokinematic treatment can also include stretching of shortened muscles, depending on clinical findings.¹¹⁴ Several studies have shown that various mobilization techniques increase ROM in subjects with CAI.^{16, 41, 50, 81, 125} Furthermore, ankle joint mobilizations may have an effect on postural control¹⁶ and on landing kinematics.²⁰

Despite contradictory results in the literature on the contribution of muscle strength to the mechanism of CAI, strength training can be considered a part of the rehabilitation paradigm. Peronei muscle strength is believed to be essential to counteract inversion moments.⁹⁴ Studies have evaluated the effect of resistance training in subjects with CAI on muscle strength and proprioception, showing contradicting results.^{28, 67, 108}

Balance training is a commonly performed and generally accepted rehabilitation modality for the treatment of both acute ankle sprains and CAI. Various studies have demonstrated the preventative effect of balance training by decreasing ankle sprain incidence.^{66, 83, 122} It is believed that balance training might improve both proprioception and neuromuscular control.²⁹ Supraspinal adaptations following balance training might lead to this improved sensorimotor control.¹¹³ Several studies also found balance training to improve postural control.^{69, 86, 107} Recent literature reviews, however, stated that, although positive findings, the current available evidence is insufficient to make a definitive conclusion on the effect of balance training on postural control.^{85, 97, 128} As of now, it also remains unclear which exercises best serve rehabilitation goals and should be included in a balance training protocol. There is a wide variety of bipodal or unipodal, static or dynamic exercises with differences in surface type, arm position, visual control, etc.⁸² Further research on the 'ideal' balance training protocol might help further improve treatment outcomes.

To prevent recurrent ankle sprains, external support such as tape or brace is also a frequently used treatment modality in subjects with CAI. Especially during those sporting activities in which high demands are imposed on the ankle joint, athletes find support in the use of external support. A study on ankle sprain incidence in high school athletes, registered a decrease in the number of ankle sprains if external support was worn.⁸⁸ The precise working mechanism, remains as of yet unclear. From a mechanical perspective, external support is intended to restrict excessive motion.^{12, 61, 89} However, an impact on sensorimotor function has also been proposed.^{90, 109}

Although several treatment modalities have been proposed in the rehabilitation of subjects with CAI, there is still uncertainty about their effectiveness. In view of the unclear multifactorial mechanism underlying CAI and unclear effect of the different treatment modalities, clinicians are left with a challenge to perform best practice when dealing with CAI.

Background and aims of this dissertation

As aforementioned, the precise underlying mechanism of CAI remains unclear and is believed to be multifactorial. Nevertheless, a better understanding of this mechanism is essential to be able to adequately treat and possibly prevent the development of CAI. Consequently, the ideal treatment protocol for subjects with CAI has not been developed yet. Further research is warranted. Therefore, the goal of this dissertation was threefold.

Aim 1: To further understanding of biomechanical contributors to the underlying mechanism of chronic ankle instability

Altered kinematics of the ankle joint during gait and landing activities have been reported to play a role in the underlying mechanisms of CAI.^{11, 22, 24, 45, 78} Based on kinetic chain theories, also the more proximal knee and the hip joints are being assessed as possible contributors to the mechanism of CAI. However, the available evidence is limited and contradicting indicating the need for more studies on lower limb biomechanics during landing tasks in order to identify underlying mechanisms of CAI. In *chapter 1*, potential lower limb kinematic deviations, i.e. at the hip, knee and ankle joint, were evaluated during a sagittal plane and frontal plane landing task in subjects with CAI. Furthermore, as aforementioned, foot characteristics may also play a role in the mechanism of CAI. Moreover, since first foot contact during landing tasks happens with the forefoot, differences in foot segment kinematics may as well influence ankle kinematics. Therefore, in addition to investigating more proximal joints in *chapter 1*, the Ghent Foot Model¹⁸ was used to evaluate multi-segment foot kinematics in subjects with CAI, respectively during gait in *chapter 2* and during a sagittal and frontal plane landing task in *chapter 3*.

Aim 2: Evaluating the effect of conservative therapeutic interventions on known contributors associated with chronic ankle instability

Since several studies have identified an impaired dynamic postural control as a contributor to CAI^{10, 102, 103, 131, 132}, various intervention modalities have been used to improve this outcome parameter.^{21, 69} It is believed that a more stable body results in a reduced incidence of recurrent lower extremity injuries emphasizing that improving postural control is an important aspect of injury prevention.¹²³ As aforementioned, a clear conclusion on the effect of balance training on postural control is not feasible based on the available literature.^{85, 97, 128} In addition, no studies have been done evaluating the effect of a

home-based balance training protocol on postural control in subjects with CAI during dynamic landing tasks, although most ankle sprains occur during landing.³⁶ Therefore, in *chapter 4*, the effect of a balance training protocol on the dynamic postural stability in subjects with CAI was evaluated during a landing task. In *chapter 5*, we investigated the effect of taping on dynamic postural control during a sagittal and frontal plane landing task in subjects with CAI. Again, no studies have yet evaluated the effect of tape, in contrast to the effect of a brace⁴⁷, on postural control during a dynamic landing task.

Aim 3: Creating rationale for designing balance training protocols

When considering a balance training protocol it remains as of yet unclear which exercises best serve the rehabilitation goal. Typically, progression in difficulty level is made using variations in performed exercises: arm position, visual control, from bipodal to unipodal, etc.⁸² In addition, most balance protocols use unstable devices without control over the direction in which the ankle is challenged. However, in a progressive treatment protocol, it might be desirable to focus on resolving deficits of specific ankle stabilizing muscles, especially in the early stages of rehabilitation. Furthermore, current knowledge on the influence of surface type on muscle activity levels is based on studies including healthy subjects.^{3, 7, 13, 126} In *chapter 6*, the effect of foot orientation on a uni-axial wobble board on activity of the ankle stabilizing muscles in healthy subjects was evaluated. Consequently, in *chapter 7*, the influence of various surface types - uni-axial as well as multidirectionally unstable devices - on activity of ankle stabilizing muscles in subjects with CAI was investigated.

References

- (1) Anandacoomarasamy A, Barnsley L. Long term outcomes of inversion ankle injuries. *Br J Sports Med* 2005;39(3):e14.
- (2) Arnold BL, De La Motte S, Linens S, Ross SE. Ankle instability is associated with balance impairments: a meta-analysis. *Med Sci Sports Exerc* 2009;41(5):1048-1062.
- (3) Bellow JW, Frilot CF, Busch SC, Lamothe TV, Ozane CJ. Facilitating activation of the peroneus longus: electromyographic analysis of exercises consistent with biomechanical function. *J Strength Cond Res* 2010;24(2):442-446.
- (4) Berkowitz MJ, Kim DH. Fibular position in relation to lateral ankle instability. *Foot Ankle Int* 2004;25(5):318-321.
- (5) Bernier JN, Perrin DH, Rijke A. Effect of unilateral functional instability of the ankle on postural sway and inversion and eversion strength. *J Athl Train* 1997;32(3):226-232.
- (6) Birmingham TB, Chesworth BM, Hartsell HD, Stevenson AL, Lapenskie GL, Vandervoort AA. Peak passive resistive torque at maximum inversion range of motion in subjects with recurrent ankle inversion sprains. *J Orthop Sports Phys Ther* 1997;25(5):342-348.
- (7) Blackburn JT, Hirth CJ, Guskiewicz KM. Exercise Sandals Increase Lower Extremity Electromyographic Activity During Functional Activities. *J Athl Train* 2003;38(3):198-203.
- (8) Boyle J, Negus V. Joint position sense in the recurrently sprained ankle. *Aust J Physiother* 1998;44(3):159-163.
- (9) Brown C. Foot clearance in walking and running in individuals with ankle instability. *Am J Sports Med* 2011;39(8):1769-1776.
- (10) Brown CN, Mynark R. Balance deficits in recreational athletes with chronic ankle instability. *J Athl Train* 2007;42(3):367-373.
- (11) Caulfield BM, Garrett M. Functional instability of the ankle: differences in patterns of ankle and knee movement prior to and post landing in a single leg jump. *Int J Sports Med* 2002;23(1):64-68.
- (12) Cordova ML, Dorrrough JL, Kious K, Ingersoll CD, Merrick MA. Prophylactic ankle bracing reduces rearfoot motion during sudden inversion. *Scand J Med Sci Sports* 2007;17(3):216-222.
- (13) Cordova M, Jutte L, Hopkins J. EMG comparison of selected ankle rehabilitation exercises. *J Sport Rehab* 1999;8:209-218.
- (14) Corti G, Costagliola P, Bonini M et al. Modelling the failure mechanisms of Michelangelo's David through small-scale centrifuge experiments. *Journal of Cultural Heritage* 2014.
- (15) Croy T, Koppenhaver S, Saliba S, Hertel J. Anterior talocrural joint laxity: diagnostic accuracy of the anterior drawer test of the ankle. *J Orthop Sports Phys Ther* 2013;43(12):911-919.
- (16) Cruz-Diaz D, Lomas VR, Osuna-Perez MC, Hita-Contreras F, Martinez-Amat A. Effects of joint mobilization on chronic ankle instability: a randomized controlled trial. *Disabil Rehabil* 2014;1-10.
- (17) David P, Halimi M, Mora I, Doutrelot PL, Petitjean M. Isokinetic Testing of Evertor and Invertor Muscles in Patients with Chronic Ankle Instability. *J Appl Biomech* 2013;29(6):696-704.
- (18) De Mits S, Segers V, Woodburn J, Elewaut D, De Clercq D, Roosen P. A clinically applicable six-segmented foot model. *J Orthop Res* 2012;30(4):655-661.
- (19) Delahunt E, Coughlan GF, Caulfield B, Nightingale EJ, Lin CW, Hiller CE. Inclusion criteria when investigating insufficiencies in chronic ankle instability. *Med Sci Sports Exerc* 2010;42(11):2106-2121.
- (20) Delahunt E, Cusack K, Wilson L, Doherty C. Joint mobilization acutely improves landing kinematics in chronic ankle instability. *Med Sci Sports Exerc* 2013;45(3):514-519.

- (21) Delahunt E, McGrath A, Doran N, Coughlan GF. Effect of taping on actual and perceived dynamic postural stability in persons with chronic ankle instability. *Arch Phys Med Rehabil* 2010;91(9):1383-1389.
- (22) Delahunt E, Monaghan K, Caulfield B. Altered neuromuscular control and ankle joint kinematics during walking in subjects with functional instability of the ankle joint. *Am J Sports Med* 2006;34(12):1970-1976.
- (23) Delahunt E, Monaghan K, Caulfield B. Changes in lower limb kinematics, kinetics, and muscle activity in subjects with functional instability of the ankle joint during a single leg drop jump. *J Orthop Res* 2006;24(10):1991-2000.
- (24) Delahunt E, Monaghan K, Caulfield B. Ankle function during hopping in subjects with functional instability of the ankle joint. *Scand J Med Sci Sports* 2007;17(6):641-648.
- (25) Denegar CR, Hertel J, Fonseca J. The effect of lateral ankle sprain on dorsiflexion range of motion, posterior talar glide, and joint laxity. *J Orthop Sports Phys Ther* 2002;32(4):166-173.
- (26) DiStefano LJ, Clark MA, Padua DA. Evidence supporting balance training in healthy individuals: a systemic review. *J Strength Cond Res* 2009;23(9):2718-2731.
- (27) Docherty CL, Arnold BL. Force sense deficits in functionally unstable ankles. *J Orthop Res* 2008;26(11):1489-1493.
- (28) Docherty CL, Moore JH, Arnold BL. Effects of strength training on strength development and joint position sense in functionally unstable ankles. *J Athl Train* 1998;33(4):310-314.
- (29) Donovan L, Hertel J. A new paradigm for rehabilitation of patients with chronic ankle instability. *Phys Sportsmed* 2012;40(4):41-51.
- (30) Drewes LK, McKeon PO, Kerrigan DC, Hertel J. Dorsiflexion deficit during jogging with chronic ankle instability. *J Sci Med Sport* 2009;12(6):685-687.
- (31) Ebig M, Lephart SM, Burdett RG, Miller MC, Pincivero DM. The effect of sudden inversion stress on EMG activity of the peroneal and tibialis anterior muscles in the chronically unstable ankle. *J Orthop Sports Phys Ther* 1997;26(2):73-77.
- (32) Eechaute C, Vaes P, Duquet W, Van GB. Reliability and discriminative validity of sudden ankle inversion measurements in patients with chronic ankle instability. *Gait Posture* 2009;30(1):82-86.
- (33) Eren OT, Kucukkaya M, Kabukcuoglu Y, Kuzgun U. The role of a posteriorly positioned fibula in ankle sprain. *Am J Sports Med* 2003;31(6):995-998.
- (34) Fernandes N, Allison GT, Hopper D. Peroneal latency in normal and injured ankles at varying angles of perturbation. *Clin Orthop Relat Res* 2000;(375):193-201.
- (35) Fong DT, Chan YY, Mok KM, Yung PS, Chan KM. Understanding acute ankle ligamentous sprain injury in sports. *Sports Med Arthrosc Rehabil Ther Technol* 2009;1:14.
- (36) Fong DT, Hong Y, Chan LK, Yung PS, Chan KM. A systematic review on ankle injury and ankle sprain in sports. *Sports Med* 2007;37(1):73-94.
- (37) Fousekis K, Tsepis E, Vagenas G. Intrinsic risk factors of noncontact ankle sprains in soccer: a prospective study on 100 professional players. *Am J Sports Med* 2012;40(8):1842-1850.
- (38) Freeman MA, Dean MR, Hanham IW. The etiology and prevention of functional instability of the foot. *J Bone Joint Surg Br* 1965;47(4):678-685.
- (39) Friel K, McLean N, Myers C, Caceres M. Ipsilateral hip abductor weakness after inversion ankle sprain. *J Athl Train* 2006;41(1):74-78.
- (40) Frigg A, Magerkurth O, Valderrabano V, Ledermann HP, Hintermann B. The effect of osseous ankle configuration on chronic ankle instability. *Br J Sports Med* 2007;41(7):420-424.
- (41) Gilbreath JP, Gaven SL, Van Lunen L, Hoch MC. The effects of mobilization with movement on dorsiflexion range of motion, dynamic balance, and self-reported function in individuals with chronic ankle instability. *Man Ther* 2014;19(2):152-157.

- (42) Goldie PA, Bach TM, Evans OM. Force platform measures for evaluating postural control: reliability and validity. *Arch Phys Med Rehabil* 1989;70(7):510-517.
- (43) Gribble P, Robinson R. Differences in spatiotemporal landing variables during a dynamic stability task in subjects with CAI. *Scand J Med Sci Sports* 2010;20(1):e63-e71.
- (44) Gribble PA, Delahunt E, Bleakley C et al. Selection criteria for patients with chronic ankle instability in controlled research: a position statement of the international ankle consortium. *J Orthop Sports Phys Ther* 2013;43(8):585-591.
- (45) Gribble PA, Robinson RH. Alterations in knee kinematics and dynamic stability associated with chronic ankle instability. *J Athl Train* 2009;44(4):350-355.
- (46) Gribble PA, Robinson RH. An examination of ankle, knee, and hip torque production in individuals with chronic ankle instability. *J Strength Cond Res* 2009;23(2):395-400.
- (47) Gribble PA, Taylor BL, Shinohara J. Bracing does not improve dynamic stability in chronic ankle instability subjects. *Phys Ther Sport* 2010;11(1):3-7.
- (48) Gross MT. Effects of recurrent lateral ankle sprains on active and passive judgements of joint position. *Phys Ther* 1987;67(10):1505-1509.
- (49) Gutierrez GM, Kaminski TW, Douex AT. Neuromuscular control and ankle instability. *PM R* 2009;1(4):359-365.
- (50) Harkey M, McLeod M, Wells A et al. The Immediate Effects of an Anterior-to-Posterior Talar Mobilization on Neural Excitability, Dorsiflexion Range of Motion, and Dynamic Balance in Patients With Chronic Ankle Instability. *J Sport Rehabil* 2014.
- (51) Harrington KD. Degenerative arthritis of the ankle secondary to long-standing lateral ligament instability. *J Bone Joint Surg Am* 1979;61(3):354-361.
- (52) Hartsell HD, Spaulding SJ. Eccentric/concentric ratios at selected velocities for the invertor and evertor muscles of the chronically unstable ankle. *Br J Sports Med* 1999;33(4):255-258.
- (53) Hass CJ, Bishop MD, Doidge D, Wikstrom EA. Chronic ankle instability alters central organization of movement. *Am J Sports Med* 2010;38(4):829-834.
- (54) Hertel J. Functional instability following lateral ankle sprain. *Sports Med* 2000;29(5):361-371.
- (55) Hertel J. Functional Anatomy, Pathomechanics, and Pathophysiology of Lateral Ankle Instability. *J Athl Train* 2002;37(4):364-375.
- (56) Hertel J. Sensorimotor deficits with ankle sprains and chronic ankle instability. *Clin Sports Med* 2008;27(3):353-70, vii.
- (57) Hiller CE, Kilbreath SL, Refshauge KM. Chronic ankle instability: evolution of the model. *J Athl Train* 2011;46(2):133-141.
- (58) Hiller CE, Nightingale EJ, Lin CW, Coughlan GF, Caulfield B, Delahunt E. Characteristics of people with recurrent ankle sprains: a systematic review with meta-analysis. *Br J Sports Med* 2011;45(8):660-672.
- (59) Hoch MC, McKeon PO. Peroneal reaction time after ankle sprain: a systematic review and meta-analysis. *Med Sci Sports Exerc* 2014;46(3):546-556.
- (60) Hopkins JT, Brown TN, Christensen L, Palmieri-Smith RM. Deficits in peroneal latency and electromechanical delay in patients with functional ankle instability. *J Orthop Res* 2009;27(12):1541-1546.
- (61) Hubbard TJ, Cordova M. Effect of ankle taping on mechanical laxity in chronic ankle instability. *Foot Ankle Int* 2010;31(6):499-504.
- (62) Hubbard TJ, Hertel J, Sherbondy P. Fibular position in individuals with self-reported chronic ankle instability. *J Orthop Sports Phys Ther* 2006;36(1):3-9.
- (63) Hubbard TJ, Hicks-Little CA. Ankle ligament healing after an acute ankle sprain: an evidence-based approach. *J Athl Train* 2008;43(5):523-529.

- (64) Hubbard TJ, Kaminski TW. Kinesthesia Is Not Affected by Functional Ankle Instability Status. *J Athl Train* 2002;37(4):481-486.
- (65) Hubbard TJ, Kramer LC, Denegar CR, Hertel J. Contributing factors to chronic ankle instability. *Foot Ankle Int* 2007;28(3):343-354.
- (66) Hupperets MD, Verhagen EA, van Mechelen W. Effect of unsupervised home based proprioceptive training on recurrences of ankle sprain: randomised controlled trial. *BMJ* 2009;339:b2684.
- (67) Kaminski TW, Buckley BD, Powers ME, Hubbard TJ, Ortiz C. Effect of strength and proprioception training on eversion to inversion strength ratios in subjects with unilateral functional ankle instability. *Br J Sports Med* 2003;37(5):410-415.
- (68) Khin MH, Ishii T, Sakane M, Hayashi K. Effect of anesthesia of the sinus tarsi on peroneal reaction time in patients with functional instability of the ankle. *Foot Ankle Int* 1999;20(9):554-559.
- (69) Kidgell DJ, Horvath DM, Jackson BM, Seymour PJ. Effect of six weeks of dura disc and mini-trampoline balance training on postural sway in athletes with functional ankle instability. *J Strength Cond Res* 2007;21(2):466-469.
- (70) Kipp K, Palmieri-Smith RM. Differences in kinematic control of ankle joint motions in people with chronic ankle instability. *Clin Biomech (Bristol , Avon)* 2013.
- (71) Konradsen L, Bech L, Ehrenbjerg M, Nickelsen T. Seven years follow-up after ankle inversion trauma. *Scand J Med Sci Sports* 2002;12(3):129-135.
- (72) Konradsen L, Magnusson P. Increased inversion angle replication error in functional ankle instability. *Knee Surg Sports Traumatol Arthrosc* 2000;8(4):246-251.
- (73) Konradsen L, Ravn JB. Prolonged peroneal reaction time in ankle instability. *Int J Sports Med* 1991;12(3):290-292.
- (74) Konradsen L, Voigt M, Hojsgaard C. Ankle inversion injuries. The role of the dynamic defense mechanism. *Am J Sports Med* 1997;25(1):54-58.
- (75) Larsen E, Angermann P. Association of ankle instability and foot deformity. *Acta Orthop Scand* 1990;61(2):136-139.
- (76) Lentell G, Baas B, Lopez D, McGuire L, Sarrels M, Snyder P. The contributions of proprioceptive deficits, muscle function, and anatomic laxity to functional instability of the ankle. *J Orthop Sports Phys Ther* 1995;21(4):206-215.
- (77) Lim EC, Tan MH. Side-to-side difference in joint position sense and kinesthesia in unilateral functional ankle instability. *Foot Ankle Int* 2009;30(10):1011-1017.
- (78) Lin CF, Chen CY, Lin CW. Dynamic ankle control in athletes with ankle instability during sports maneuvers. *Am J Sports Med* 2011;39(9):2007-2015.
- (79) Lofvenberg R, Karrholm J, Sundelin G, Ahlgren O. Prolonged reaction time in patients with chronic lateral instability of the ankle. *Am J Sports Med* 1995;23(4):414-417.
- (80) Magerkurth O, Frigg A, Hintermann B, Dick W, Valderrabano V. Frontal and lateral characteristics of the osseous configuration in chronic ankle instability. *Br J Sports Med* 2010;44(8):568-572.
- (81) Marron-Gomez D, Rodriguez-Fernandez AL, Martin-Urrialde JA. The effect of two mobilization techniques on dorsiflexion in people with chronic ankle instability. *Phys Ther Sport* 2014; doi: 10.1016/j.ptsp.2014.02.001. [Epub ahead of print]
- (82) Mattacola CG, Dwyer MK. Rehabilitation of the Ankle After Acute Sprain or Chronic Instability. *J Athl Train* 2002;37(4):413-429.
- (83) McGuine TA, Keene JS. The effect of a balance training program on the risk of ankle sprains in high school athletes. *Am J Sports Med* 2006;34(7):1103-1111.

- (84) McKeon PO, Hertel J. Systematic review of postural control and lateral ankle instability, part I: can deficits be detected with instrumented testing. *J Athl Train* 2008;43(3):293-304.
- (85) McKeon PO, Hertel J. Systematic review of postural control and lateral ankle instability, part II: is balance training clinically effective? *J Athl Train* 2008;43(3):305-315.
- (86) McKeon PO, Ingersoll CD, Kerrigan DC, Saliba E, Bennett BC, Hertel J. Balance training improves function and postural control in those with chronic ankle instability. *Med Sci Sports Exerc* 2008;40(10):1810-1819.
- (87) McVey ED, Palmieri RM, Docherty CL, Zinder SM, Ingersoll CD. Arthrogenic muscle inhibition in the leg muscles of subjects exhibiting functional ankle instability. *Foot Ankle Int* 2005;26(12):1055-1061.
- (88) Mickel TJ, Bottoni CR, Tsuji G, Chang K, Baum L, Tokushige KA. Prophylactic bracing versus taping for the prevention of ankle sprains in high school athletes: a prospective, randomized trial. *J Foot Ankle Surg* 2006;45(6):360-365.
- (89) Miller H, Needle AR, Swanik CB, Gustavsen GA, Kaminski TW. Role of external prophylactic support in restricting accessory ankle motion after exercise. *Foot Ankle Int* 2012;33(10):862-869.
- (90) Miralles I, Monterde S, Montull S, Salvat I, Fernandez-Ballart J, Beceiro J. Ankle taping can improve proprioception in healthy volunteers. *Foot Ankle Int* 2010;31(12):1099-1106.
- (91) Monaghan K, Delahunt E, Caulfield B. Ankle function during gait in patients with chronic ankle instability compared to controls. *Clin Biomech (Bristol , Avon)* 2006;21(2):168-174.
- (92) Monteleone BJ, Ronsky JL, Meeuwisse WH, Zernicke RF. Ankle Kinematics and Muscle Activity in Functional Ankle Instability. *Clin J Sport Med* 2013.
- (93) Morrison KE, Kaminski TW. Foot characteristics in association with inversion ankle injury. *J Athl Train* 2007;42(1):135-142.
- (94) Munn J, Beard DJ, Refshauge KM, Lee RY. Eccentric muscle strength in functional ankle instability. *Med Sci Sports Exerc* 2003;35(2):245-250.
- (95) Needle AR, Charles BB, Farquhar WB, Thomas SJ, Rose WC, Kaminski TW. Muscle spindle traffic in functionally unstable ankles during ligamentous stress. *J Athl Train* 2013;48(2):192-202.
- (96) Nelson AJ, Collins CL, Yard EE, Fields SK, Comstock RD. Ankle injuries among United States high school sports athletes, 2005-2006. *J Athl Train* 2007;42(3):381-387.
- (97) O'Driscoll J, Delahunt E. Neuromuscular training to enhance sensorimotor and functional deficits in subjects with chronic ankle instability: A systematic review and best evidence synthesis. *Sports Med Arthrosc Rehabil Ther Technol* 2011;3:19.
- (98) Rankine L, Long J, Canseco K, Harris GF. Multisegmental foot modeling: a review. *Crit Rev Biomed Eng* 2008;36(2-3):127-181.
- (99) Riemann BL. Is There a Link Between Chronic Ankle Instability and Postural Instability? *J Athl Train* 2002;37(4):386-393.
- (100) Riemann BL, Lephart SM. The sensorimotor system, part I: the physiologic basis of functional joint stability. *J Athl Train* 2002;37(1):71-79.
- (101) Rosen AB, Ko J, Brown CN. Diagnostic accuracy of instrumented and manual talar tilt tests in chronic ankle instability populations. *Scand J Med Sci Sports* 2014; doi: 10.1111/sms.12288. [Epub ahead of print]
- (102) Ross SE, Guskiewicz KM. Examination of static and dynamic postural stability in individuals with functionally stable and unstable ankles. *Clin J Sport Med* 2004;14(6):332-338.
- (103) Ross SE, Guskiewicz KM, Yu B. Single-leg jump-landing stabilization times in subjects with functionally unstable ankles. *J Athl Train* 2005;40(4):298-304.

- (104) Santilli V, Frascarelli MA, Paoloni M et al. Peroneus longus muscle activation pattern during gait cycle in athletes affected by functional ankle instability: a surface electromyographic study. *Am J Sports Med* 2005;33(8):1183-1187.
- (105) Santos MJ, Liu W. Possible factors related to functional ankle instability. *J Orthop Sports Phys Ther* 2008;38(3):150-157.
- (106) Sedory EJ, McVey ED, Cross KM, Ingersoll CD, Hertel J. Arthrogenic muscle response of the quadriceps and hamstrings with chronic ankle instability. *J Athl Train* 2007;42(3):355-360.
- (107) Sefton JM, Yarar C, Hicks-Little CA, Berry JW, Cordova ML. Six weeks of balance training improves sensorimotor function in individuals with chronic ankle instability. *J Orthop Sports Phys Ther* 2011;41(2):81-89.
- (108) Sekir U, Yildiz Y, Hazneci B, Ors F, Aydin T. Effect of isokinetic training on strength, functionality and proprioception in athletes with functional ankle instability. *Knee Surg Sports Traumatol Arthrosc* 2007;15(5):654-664.
- (109) Simon J, Garcia W, Docherty CL. The effect of kinesio tape on force sense in people with functional ankle instability. *Clin J Sport Med* 2014;24(4):289-294.
- (110) Suda EY, Amorim CF, Sacco IC. Influence of ankle functional instability on the ankle electromyography during landing after volleyball blocking. *J Electromyogr Kinesiol* 2009;19(2):e84-e93.
- (111) Suda EY, Sacco IC. Altered leg muscle activity in volleyball players with functional ankle instability during a sideward lateral cutting movement. *Phys Ther Sport* 2011;12(4):164-170.
- (112) Swenson DM, Collins CL, Fields SK, Comstock RD. Epidemiology of U.S. high school sports-related ligamentous ankle injuries, 2005/06-2010/11. *Clin J Sport Med* 2013;23(3):190-196.
- (113) Taube W, Gruber M, Gollhofer A. Spinal and supraspinal adaptations associated with balance training and their functional relevance. *Acta Physiol (Oxf)* 2008;193(2):101-116.
- (114) Terada M, Pietrosimone BG, Gribble PA. Therapeutic interventions for increasing ankle dorsiflexion after ankle sprain: a systematic review. *J Athl Train* 2013;48(5):696-709.
- (115) Terada M, Pietrosimone BG, Gribble PA. Alterations in Neuromuscular Control at the Knee in Individuals With Chronic Ankle Instability. *J Athl Train* 2014.
- (116) Vaes P, Duquet W, Van Gheluwe B. Peroneal Reaction Times and Eversion Motor Response in Healthy and Unstable Ankles. *J Athl Train* 2002;37(4):475-480.
- (117) Valderrabano V, Hintermann B, Horisberger M, Fung TS. Ligamentous posttraumatic ankle osteoarthritis. *Am J Sports Med* 2006;34(4):612-620.
- (118) Valmassy R. *Clinical biomechanics of the lower extremities*. 2012.
- (119) Van Bergeyk AB, Younger A, Carson B. CT analysis of hindfoot alignment in chronic lateral ankle instability. *Foot Ankle Int* 2002;23(1):37-42.
- (120) van Rijn RM, van Os AG, Bernsen RM, Luijsterburg PA, Koes BW, Bierma-Zeinstra SM. What is the clinical course of acute ankle sprains? A systematic literature review. *Am J Med* 2008;121(4):324-331.
- (121) Van Deun S, Staes FF, Stappaerts KH, Janssens L, Levin O, Peers KK. Relationship of chronic ankle instability to muscle activation patterns during the transition from double-leg to single-leg stance. *Am J Sports Med* 2007;35(2):274-281.
- (122) Verhagen E, van der Beek A, Twisk J, Bouter L, Bahr R, van Mechelen W. The effect of a proprioceptive balance board training program for the prevention of ankle sprains: a prospective controlled trial. *Am J Sports Med* 2004;32(6):1385-1393.
- (123) Verhagen E, van der Beek A, Twisk J, Bouter L, Bahr R, van Mechelen W. The effect of a proprioceptive balance board training program for the prevention of ankle sprains: a prospective controlled trial. *Am J Sports Med* 2004;32(6):1385-1393.

- (124) Verhagen EA, van Tulder M, van der Beek AJ, Bouter LM, van Mechelen W. An economic evaluation of a proprioceptive balance board training programme for the prevention of ankle sprains in volleyball. *Br J Sports Med* 2005;39(2):111-115.
- (125) Vicenzino B, Branjerdporn M, Teys P, Jordan K. Initial changes in posterior talar glide and dorsiflexion of the ankle after mobilization with movement in individuals with recurrent ankle sprain. *J Orthop Sports Phys Ther* 2006;36(7):464-471.
- (126) Wahl MJ, Behm DG. Not all instability training devices enhance muscle activation in highly resistance-trained individuals. *J Strength Cond Res* 2008;22(4):1360-1370.
- (127) Waterman BR, Belmont PJ, Jr., Cameron KL, Svoboda SJ, Alitz CJ, Owens BD. Risk factors for syndesmotic and medial ankle sprain: role of sex, sport, and level of competition. *Am J Sports Med* 2011;39(5):992-998.
- (128) Webster KA, Gribble PA. Functional rehabilitation interventions for chronic ankle instability: a systematic review. *J Sport Rehabil* 2010;19(1):98-114.
- (129) Webster KA, Gribble PA. A comparison of electromyography of gluteus medius and maximus in subjects with and without chronic ankle instability during two functional exercises. *Phys Ther Sport* 2013;14(1):17-22.
- (130) Wikstrom EA, Hubbard TJ. Talar positional fault in persons with chronic ankle instability. *Arch Phys Med Rehabil* 2010;91(8):1267-1271.
- (131) Wikstrom EA, Tillman MD, Borsa PA. Detection of dynamic stability deficits in subjects with functional ankle instability. *Med Sci Sports Exerc* 2005;37(2):169-175.
- (132) Wikstrom EA, Tillman MD, Chmielewski TL, Cauraugh JH, Borsa PA. Dynamic postural stability deficits in subjects with self-reported ankle instability. *Med Sci Sports Exerc* 2007;39(3):397-402.
- (133) Willems T, Witvrouw E, Verstuyft J, Vaes P, De Clercq D. Proprioception and Muscle Strength in Subjects With a History of Ankle Sprains and Chronic Instability. *J Athl Train* 2002;37(4):487-493.
- (134) Winter DA. Human balance and posture control during standing and walking. *Gait Posture* 1995.
- (135) Wolfe MW, Uhl TL, Mattacola CG, McCluskey LC. Management of ankle sprains. *Am Fam Physician* 2001;63(1):93-104.
- (136) Zhang SN, Bates BT, Dufek JS. Contributions of lower extremity joints to energy dissipation during landings. *Med Sci Sports Exerc* 2000;32(4):812-819.

Lower limb landing biomechanics in subjects with chronic ankle instability

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Abstract:

Objective: Literature on lower limb kinematic deviations in subjects with chronic ankle instability (CAI) during landing tasks is limited and not consistent. Several studies only report joint angles at defined events rather than considering the whole kinematic curve which might obscure possibly relevant information. Therefore, the main goal of this study was to evaluate landing kinematics of the lower limb in subjects with CAI using curve analysis.

Methods: Lower limb kinematics of 56 subjects (28 subjects with self-reported CAI and 28 matched healthy controls) were measured during a barefoot forward and side jump protocol. Kinematic data were collected in a laboratory setting using an eight-camera optoelectronic system. Ground reaction forces were registered by means of a force plate built into the landing zone. After completion of each task, difficulty level and subjective stability at the ankle joint were documented using a visual analogue scale. To compare between groups, Statistical Parametric Mapping was used to assess group differences between mean joint angles over the entire impact phase.

Results: SPM analysis of kinematical curves of the hip, knee, and ankle showed no significant differences between the subjects with CAI and the control group independent of jump direction. Subjects with CAI did report higher feelings of instability for both landing tasks and a higher difficulty level for the forward jump.

Conclusion: Our results showed no altered lower limb kinematics in subjects with CAI compared to a healthy control group during a forward and side jump landing task. Therefore, these results question the hypothesis of kinematic deviations as part of an underlying mechanism of CAI.

Introduction

A recent systematic review with meta-analysis on ankle sprain epidemiology calculated a cumulative incidence rate between 6.94 (males) and 13.6 (females) sprains per 1000 exposures, with the highest incidence for indoor or court sports.¹⁰ Although an ankle sprain is considered a common temporary musculoskeletal injury, a relatively high proportion of those patients develop chronic ankle instability (CAI). CAI is characterized by recurrent ankle sprains, 'giving way', and feelings of instability at the ankle joint, whether or not combined with mechanical laxity.¹⁶ In addition, CAI has been associated with a decreased level of sports participation and the development of ankle osteoarthritis.^{2, 25, 35} As for now, an unclear mechanism of combined proprioceptive deficits, neuromuscular changes, muscle strength, postural control and central adaptations is believed to be the origin of this pathology.^{19, 20}

In subjects with CAI, lower limb kinematics during dynamic landing situations are being used to evaluate the presence of kinematic deviations at the ankle joint, as well as at the more proximal knee and hip joints.^{4, 8, 18} The additional evaluation of proximal joints is based on kinetic chain theories, which stresses the interplay between proximal and distal segments during functional activities. Recently, studies focusing on proximal factors have identified relationships between proximal dysfunctions and lower extremity injuries.^{5, 37} Furthermore, biomechanical research has indicated that joint kinematics are influential in the capability of modifying and absorbing impact forces during landing tasks.⁴⁰ Therefore, kinematic adaptations might be inefficient to deal with the rapid and very high loading forces, possibly increasing the susceptibility for injury, e.g. in chronic ankle instability

Literature on proximal kinematic deviations in subjects with CAI during landing tasks is limited and not consistent. Nine relevant studies have been identified reporting divergent results. Table 1 outlines an overview of these studies on this topic which illustrates the diversity in design and results. At the level of the hip, Delahunt et al. were the only to identify less external rotation in the prelanding phase during a vertical drop in subjects with CAI⁸. Both higher and lower degree of knee flexion have been identified during a landing task^{4, 15} as well as no significant differences at all.^{8, 9} Even at the ankle joint, where studies have confirmed the hypothesis of a more inverted and plantar flexed position of the foot^{8, 9}, controversy remains with opposing results.^{24, 28} Since several studies only report joint angles at defined events during dynamic tasks^{4, 15, 18, 23, 24, 26, 28} instead of considering the whole kinematic curve this might result in a focus bias and obscure possibly relevant information.³⁰ The limited and contradicting evidence from the available literature indicates the need for more studies

Table 1. Literature overview on lower limb kinematics during landing tasks in subjects with CAI compared to controls

Author	Task	Planes	Time frame	Ankle	Knee	Hip
Caulfield et al.(4)	Vertical drop	S	(-)100ms-(+)200ms	↑ DF ((-)10ms-(+)20ms)	↑ FL ((-)20ms- (+)60ms)	/
Delahunt et al.(8)	Vertical drop	F+S+T	(-)200ms-(+)200ms	↑ INV ((-)200ms-(-)95ms), ↓ DF ((+)90-(+)200ms)	NS	↓ EXT ROT ((-)200-(-)55ms)
Delahunt et al.(9)	Lateral hop	F+S+T	(-)200ms-(+)200ms	↓ EV ((-)45ms-(+)95ms)	NS	NS
Gribble et al.(15)	Forward jump	S	(-)100ms, TD, peak	NS	↓ FL	NS
Gribble et al.(18)	Forward jump	S	TD	NS	↓ FL	NS
Kipp et al. (23)	Forward jump	F+S	TD, peak	NS	/	/
Kipp et al.(24)	Land-and-cut	F+S+T	TD, peak	NS	/	/
Lin et al.(26)	Stop jump (bilat)	F+S+T	(-)200ms-(+)200ms	↑ INV (at (+)140ms)	/	/
Monteleone et al.(28)	Med/lat hop	F+S+T	8 timepoints during flight and landing	NS	/	/

F=Frontal, S=Sagittal, T=Transversal, TD=Touch down, (-) indicates prior to TD, (+) indicates after TD, DF=Dorsiflexion, PF=Plantar flexion, INV=Inversion, EV=Eversion, EXT ROT=External rotation, ↑ indicates 'more' in subjects with CAI compared to controls, ↓ indicates 'less' in subjects with CAI compared to controls, NS signifies no significant differences between groups, / signifies not measured in the study

focusing on overall lower limb biomechanics during dynamic landing tasks in order to identify underlying mechanisms for CAI.

The main goal of the current study was to evaluate landing kinematics at the ankle, knee and hip joints in subjects with CAI compared to a healthy control group during a frontal plane and sagittal plane directed task. To avoid focus bias, the use of statistical parametric mapping (SPM), extensively used in brain research^{13, 22, 32} enabled us to perform a comprehensive curve analysis during the whole pre- and post landing phase.

Methods

Population

A total of 56 subjects participated in this study, including 28 subjects with CAI (10 men and 18 women) and 28 healthy controls (10 men and 18 women). Population characteristics are presented in table 2. Subjects in the CAI group met all of the following inclusion criteria: a history of a significant ankle sprain resulting in participation limitations for at least 3 weeks, repetitive ankle sprains, episodes of giving way, and feelings of instability and weakness around the ankle joint. The healthy control group had no history of an ankle sprain. Exclusion criteria were fractures or surgery at the ankle joint in the past. Overall, subjects were at least recreationally active defined by a minimum of 1.5 hours of cardiovascular activity a week and had no lower limb complaints at the moment of testing. Subjects of the control group were matched to subjects with CAI based on age, sex, height, weight and limb dominance. This study was approved by the ethics committee of the Ghent university hospital and all subjects signed the informed consent before participation.

Table 2. Subject characteristics

	CAI (n=28)	Control (n=28)
Age (yrs)	22.3 (2.7)	22.5 (1.6)
Height (m)	1.73 (0.10)	1.72 (0.10)
Weight (kg)	71.0 (10.6)	66.5 (9.4)
BMI	23.8 (2.8)	22.5 (2.1)
FADI (%)	88.2 (7.2)	99.7 (0.7)*
FADI-S (%)	69.9 (9.6)	99.4 (1.5)*
Time to last sprain (months)	4.5 (4.2)	N/A
Duration of complaints last sprain (weeks)	5.2 (6.1)	N/A
# sprains annually	5.6(3.6)	N/A
Ankle orthotics (tape/brace) during sports	19/28	1/28
Insoles	7/28	6/28

BMI=Body Mass Index; FADI=Foot and Ankle Disability Index; FADI-S=Foot and Disability Index Sports subscale; * signifies significant group difference with $p < 0.001$)

Instruments

Kinematic data were collected in a laboratory setting using an eight-camera optoelectronic system (250Hz, OQUS 3, Qualisys). Ground reaction forces were registered by means of a force plate (250Hz, Advanced Mechanical Technology, Inc., Watertown, MA) built into the landing zone.

Experimental procedure

Baseline anthropometric characteristics of all subjects were registered at the beginning of the testing procedure. All subjects completed a medical questionnaire, the foot and ankle disability index (FADI) and its sports subscale (FADI-S). In case of bilateral ankle instability, the most unstable ankle was selected for analysis in our study protocol based on the subject's subjective indication. To match the tested ankle of an individual control subject to a subject with CAI, limb dominance was taken into account (i.e. if the non-dominant ankle was selected for the subject with CAI, in accordance the non-dominant ankle was included for the matched control subject).

The functional protocol used in the current study is based on the study of Sell et al.³⁴ All tasks were performed barefooted. First, subjects performed a forward jump with a jump distance standardized to 40% of subject's height while jumping over a 30cm high hurdle. Push off had to be performed on both feet while subjects were instructed to land on the tested ankle on an indicated spot on the force plate. Hands were free during the flight phase, but had to be placed on the hips immediately after landing and balance had to be maintained for 5 seconds. Maintaining balance was defined by keeping the hands on the hips, no shifts of the tested ankle and no contact between the contralateral limb and the tested limb nor with the ground. Secondly, a lateral side jump was performed over a distance of 33% of subject's height over a 15cm high hurdle. Prerequisites were identical to that of the forward jump. For each task 5 successful trials were captured. After completion of each task, difficulty level and subjective stability at the ankle joint were documented using a visual analogue scale (VAS).

Kinematic data were collected using the 'Liverpool John Moores University' (LJMU) model.³⁶ This model tracks feet, upper and lower legs, pelvis and trunk. However, the trunk was not included in the current study. To track these 7 segments, 38 spherical reflective markers were placed on anatomical landmarks, along with tracking markers according to the LJMU model. A static trial was performed to define the model. Separate trials were performed for calculation of the functional hip joint centres³³ and knee joint axes.^{3, 31}

Data analysis

Kinematic and kinetic data was processed using Visual 3D (C-motion, Germantown, MD). Inter-joint motion was calculated using Euler rotations (X-Y-Z).³⁹ Rotation around the X-, Y- and Z-axis defined respectively flexion/extension (hip and knee joint) and plantar-/dorsiflexion (ankle joint) in the sagittal plane, ab-/adduction (hip and knee joint) and in-/eversion (ankle joint) in the frontal plane, and internal/external rotation (hip and knee joint) and ab-/adduction (ankle joint) in the transversal plane. The time interval for analysis extended from 200ms prior to touch down (TD) and 200ms after. Event detection was based on the vertical component of the ground reaction force (threshold set at 15 N). Marker data was filtered using a fourth order Butterworth low-pass filter at 15Hz. The raw force data were filtered by a critically damped low-pass filter at 15Hz.

A curve analysis, one-dimensional statistical parametric mapping (SPM)^{12, 29}, of mean joint angles of the ankle, knee and hip during the impact phase was performed to compare between groups. SPM allows the calculation of the traditional t statistics, subsequently referred to SPM{t}, over the entire normalized time-series. For this analysis, two-sample t-tests were performed, with $\alpha=0.05$ corrected to 0.0055 for each joint ($n=3$) and plane ($n=3$) to maintain the family-wise error rate. Firstly, SPM{t} statistic was calculated from the mean joint angles for the entire impact phase.²⁹ Secondly, the temporal smoothness of SPM{t} based on its average temporal gradient was estimated.¹² Subsequently, the threshold of SPM{t} was computed using Random Field Theory¹ above which only $\alpha=0.55\%$ of the data would be expected to reach had the test statistic trajectory resulted from an equally smooth random process. Any clusters of SPM{t} that exceeded this threshold were considered significantly different. Individual probability values were calculated for each supra-threshold cluster, which indicate the probability that a cluster of a given height and size could have resulted from an equivalently smooth random process. All SPM analyses were implemented in Python 2.7 using Canopy 1.1 (Enthought Inc., Austin, USA).

Results

SPM analysis of kinematical curves of the hip, knee, and ankle showed no significant differences between the subjects with CAI and the control group independent of jump direction. Figure 1 and 2 illustrate joint kinematics and statistical results of respectively the forward jump and the side jump.

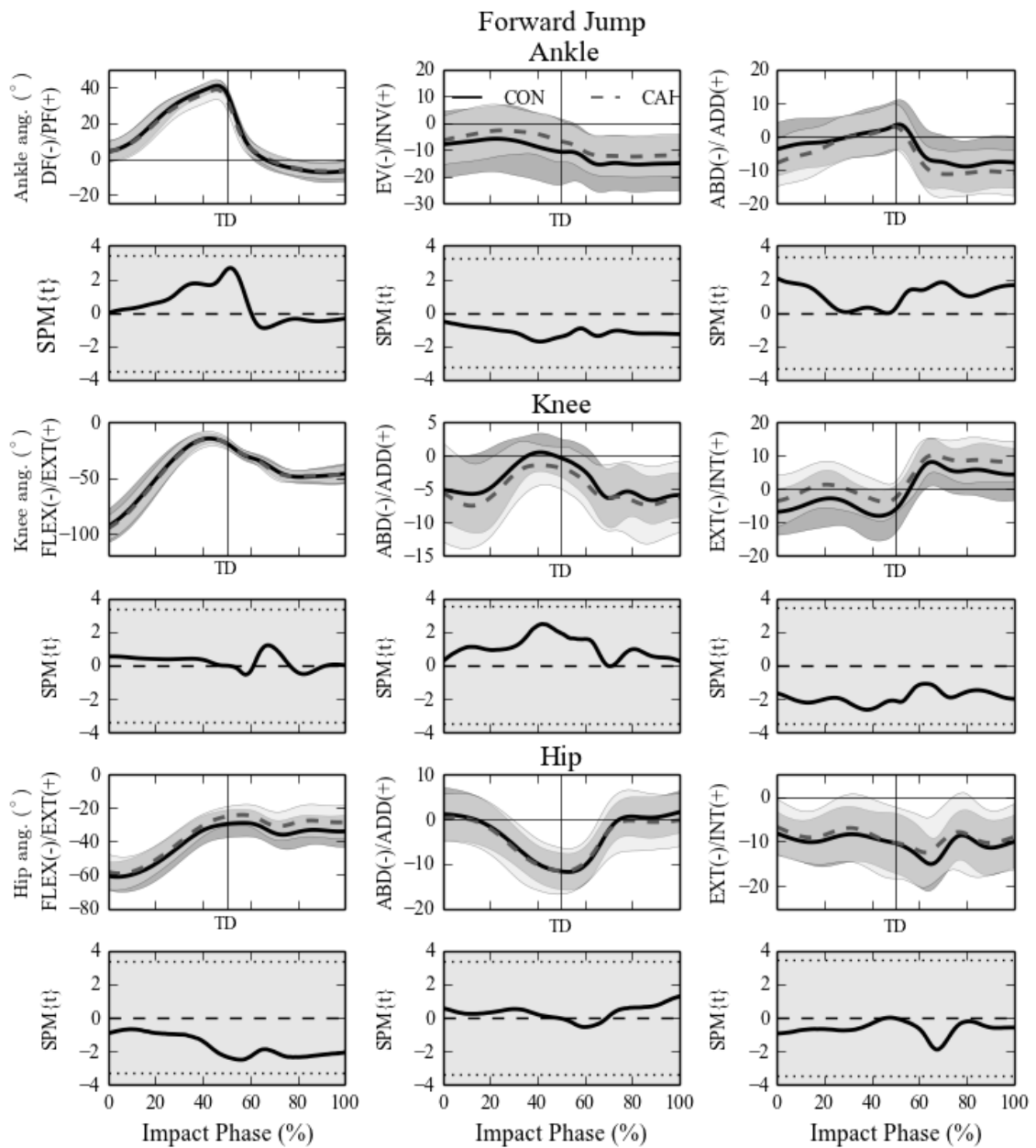


Figure 1. Lower limb kinematic comparison during the forward jump (CAI =dashed --; CON =solid _). Mean kinematic trajectories with standard deviation clouds with underneath the Statistical Parametric Mapping results are presented for each joint. "SPM{t}" is the trajectory Student's t statistic or, equivalently, the mean difference curve normalised by sample-size normalised variance. The dotted horizontal line indicates the random field theory threshold for significance. Any clusters of SPM{t} that exceeded this threshold were considered significantly different. No significant findings were reported. DF=dorsiflexion; PF=plantar flexion; FLEX=flexion; EXT=extension; EV=eversion; INV=inversion; ABD=abduction; ADD=adduction; EXT=external rotation; INT=internal rotation;TD=touch down.

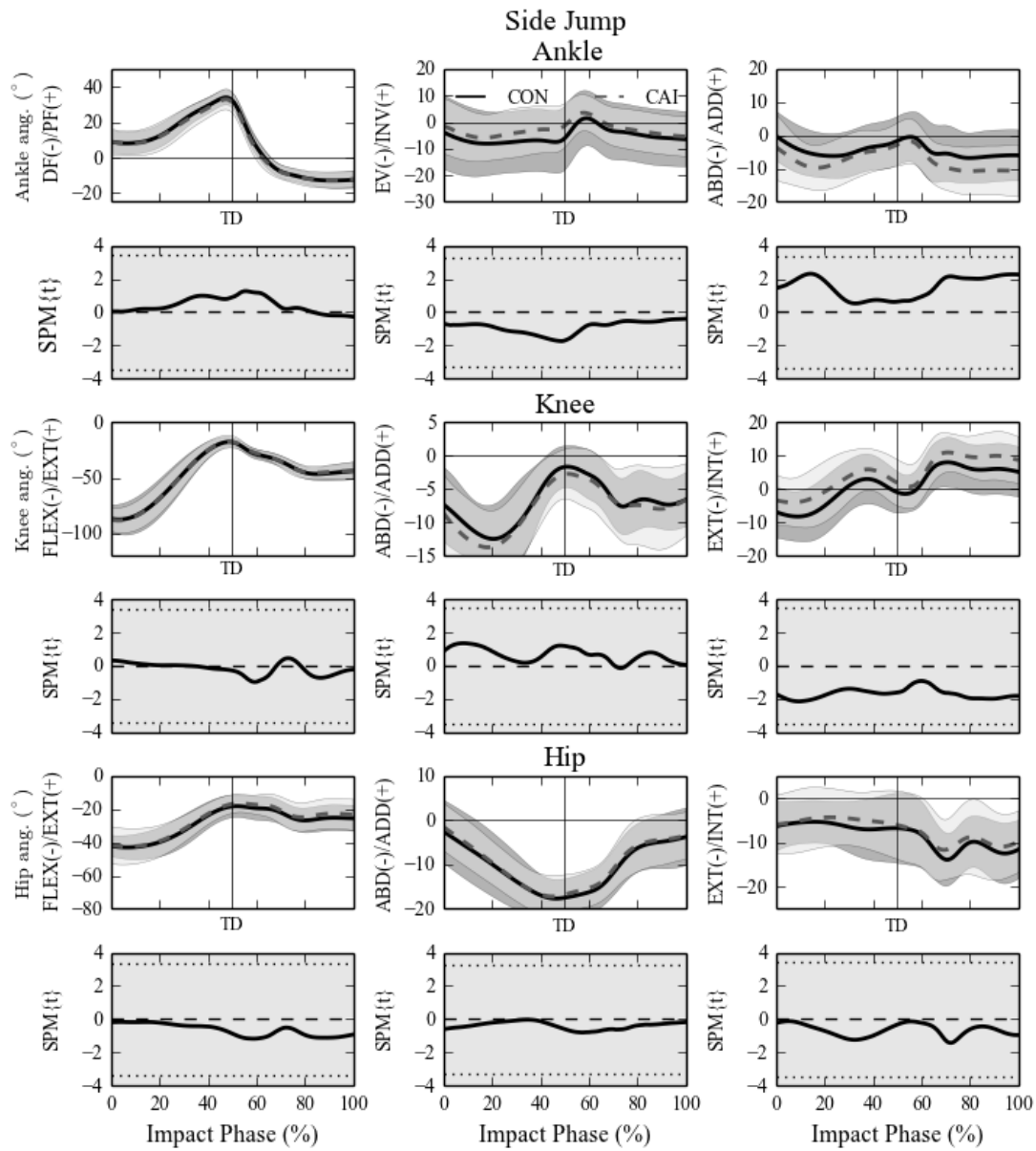


Figure 2. Lower limb kinematic comparison during the side jump (CAI =dashed --; CON =solid __). Mean kinematic trajectories with standard deviation clouds with underneath the Statistical Parametric Mapping results are presented for each joint. "SPM{t}" is the trajectory Student's t statistic.

No group differences ($p > 0.05$) were found for any of the anthropometric variables or for the amount of trials needed to complete 5 successful trials for both the forward jump (CON: 9.8 (3.3), CAI: 10.6 (3.7)) and the side jump (CON: 9.6 (2.8), CAI: 8.6 (2.6)). VAS score analysis showed that subjects with CAI had higher feelings of instability in the ankle joint for both jump directions compared to the control group (forward jump: CAI: 4.55 (2.17) cm, CON: 0.54 (0.99) cm, $p < 0.001$; side jump: CAI: 4.28 (2.09) cm, CON: 0.49 (0.95) cm, $p < 0.001$). The perceived difficulty level of the landing task was significantly higher in subjects with CAI compared to the control group for the forward jump (CAI: 4.71 (2.04) cm, CON: 2.62 (1.68), $p < 0.001$) but not for the side jump (CAI: 3.58 (2.32) cm, CON: 2.53 (1.91), $p = 0.069$).

Discussion

The goal of our study was to present a comprehensive overview of lower limb kinematics of the hip, knee and ankle during both a forward jump and side jump landing task. Instead of focusing on particular time frames, the whole landing curve ranging from 200ms pre landing till 200ms post landing, including all three motion planes, was considered for analysis using SPM, accounting for curve smoothness and corrected for multiple testing. The main results of our study revealed that there were no significant differences in lower limb kinematics between subjects with CAI and healthy controls during the imposed tasks. This raises the question on the role of lower limb kinematics in the mechanism of chronic ankle instability. Exploring the available evidence in literature reveals the large diversity of included tasks, analyzed planes, time frames and, maybe most importantly, kinematic results (table 1).

In general, the observed absence of kinematical deviations at the level of the hip coincides with most of the scarcely available literature. We identified only four studies that evaluated hip kinematics during a landing task^{8, 9, 15, 18} and only two of these analyzed all three motion planes before and after landing.^{8, 9} One study of the latter two, by Delahunt et al.⁸, reported less external rotation of the hip joint in the pre-landing phase during a vertical drop task. These authors attributed their finding to possible proximal neuromuscular impairments through central neural adaptations. However, a direct link between such impairments and altered kinematics has not been established yet. Our results are in agreement with all other studies evaluating hip kinematics during a landing tasks^{9, 15, 18} as well as during gait.^{7, 27} At this moment, available evidence does not support the involvement of deviating hip joint kinematics in the mechanism associated with CAI.

At the level of the knee, Caulfield et al. were the first to report kinematic deviations.⁴ They found more knee flexion around touch down in subjects with CAI during a vertical drop task and attributed their findings also to central adaptation. These results, however, have not been confirmed since. On the opposite, Gribble et al. found less knee flexion prior to and at touch down during a forward jump task in subjects with CAI compared to a control group.^{15, 18} They argued that a greater knee extension results in a longer period to dissipate forces after impact accounting for the increased time to stabilization they also observed. These studies of Caulfield et al. and Gribble et al. only considered the sagittal plane motion in their study design. As already indicated, our study results support neither of these findings on deviating knee kinematics during both a forward and side jump in all planes of motion, which is in agreement with Delahunt et al.^{8, 9} Two additional studies on gait also reported no kinematic deviations at the knee joint^{7, 27}, whereas Drewes et al. found an increased external rotation of the shank during large portion of the gait cycle during both walking and running.¹¹ In summary, all deviating kinematic findings at the knee joints have not been confirmed in other studies prohibiting a clear message. Notwithstanding some studies support the involvement of the knee joint in those with CAI, these study results lack confirmation by e.g. our study results. More high quality studies are needed to be able to formulate a comprehensive message on the involvement of the knee joint in CAI.

In our study, no significant differences in ankle kinematics were identified in all planes of motion during both jump protocols. In literature, we identified 9 studies in which patients with CAI performed a landing task^{4, 8, 9, 15, 18, 23, 24, 26, 28} describing ankle kinematics (see table 1). In the frontal plane, three landing studies reported an increased inversion angle in subjects with CAI. However these finding were found during different time periods of the landing phase, ranging from before touch down (200ms-95ms pre) during a vertical drop⁸, around touch down (45ms pre - 95ms post) during a lateral hop⁹, and in the post landing phase (at 140ms post) during a stop jump²⁶ (table 1). In agreement with our results, three studies described no significant frontal plane differences, i.e. during a mediolateral hop task²⁸, a forward jump²³ and a land-and-cut task²³. In the sagittal plane, a more dorsiflexed ankle position has been described around touch down by Caulfield et al.⁴, however this was not confirmed in other studies. In addition, one study by Delahunt et al. described a less dorsiflexed ankle position at the end of the landing phase indicating a lesser closed packed position.⁸ Overall, no differences have been reported on ankle kinematics in the transversal plane. Although Kipp and Palmieri-Smith found no differences in discrete ankle joint angles as aforementioned, they did find a higher inter-trial variability in the frontal and sagittal plane during a forward jump²³, and also a more complex control strategy represented by a more

planar angular co-variation during a land-and-cut task²⁴ at the ankle joint using principal component analysis. These authors associated their findings to the mechanism of CAI. Future research should consider similar approaches to reveal motion patterns associated with CAI. In general, when considering all available evidence on ankle kinematics during landing tasks, it appears difficult to generalize individual study results on ankle joint kinematics in chronic ankle instability.

Based on the current available literature, it is difficult to make a general statement on the influence of lower limb kinematics in the mechanism associated with CAI. For each joint, different results have been reported or similar results in different timeframes during the event. Differences in the inclusion criteria between studies used to select subjects with CAI might partly account for these differences. Recently, the International Ankle Consortium has endorsed a number of inclusion and exclusion criteria in an attempt to guide future research on CAI. Although our study criteria were defined before this position statement, we believe our inclusion criteria to be to a large extent in line with the endorsed criteria (i.e. (1) significant ankle sprain, (2) 'giving way', recurrent sprains and feelings of instability, and (3) a self-reported foot and ankle function questionnaire). Furthermore, studies differ in included landing tasks, kinematic registration protocols and statistical analysis making comparison difficult. An overall limiting factor could be that, when looking at kinematics, only successful trials have been taken into account and that due to technical limitations data is gathered in a laboratory setting. This means that subjects are focused on the task at hand despite distractions or perturbations sometimes used. As subjects with CAI do not experience episodes of giving way continuously, the execution of this controlled landing task might obscure possible kinematic differences between subjects with CAI and healthy controls. It might be necessary to place the system into a state in which it is more challenged, i.e. a near episode of giving way. Although our study results did indicate higher feelings of instability and difficulty level during the performed tasks in subjects with CAI, no differences were found in lower limb kinematics. These subjective scales might not reflect the actual challenge imposed on the neuromuscular system or the actual challenge might not be discriminative in joint kinematics. Maybe induced fatigue is meaningful to be able to detect kinematic deviations during landing tasks.^{6, 17} Also looking further into failed trials or kinematic control strategies might yield valuable information on CAI associated mechanisms.^{14, 24, 38} Furthermore, although CAI has been associated with impaired proprioception, strength, and (supra)spinal motor control, a direct link between such impairments and altered kinematics has not been established yet.^{19, 21} Therefore, more research is necessary to elucidate the role of lower limb kinematics in CAI.

Conclusion

The goal of our study was to provide a comprehensive overview of lower limb kinematics in subjects with CAI. Our results showed no altered lower limb kinematics in subjects with CAI compared to a healthy control group during a forward jump and side jump landing task. Therefore, these results do not support the hypothesis of kinematical deviations as part of a mechanism associated with CAI at this time.

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References

- (1) Adler RJ, Taylor JE. Random Fields and Geometry. Springer-Verlag. New York; 2007.
- (2) Anandacoomarasamy A, Barnsley L. Long term outcomes of inversion ankle injuries. *Br J Sports Med* 2005;39(3):e14.
- (3) Besier TF, Sturnieks DL, Alderson JA, Lloyd DG. Repeatability of gait data using a functional hip joint centre and a mean helical knee axis. *J Biomech* 2003;36(8):1159-1168.
- (4) Caulfield BM, Garrett M. Functional instability of the ankle: differences in patterns of ankle and knee movement prior to and post landing in a single leg jump. *Int J Sports Med* 2002;23(1):64-68.
- (5) Chuter VH, Janse de Jonge XA. Proximal and distal contributions to lower extremity injury: a review of the literature. *Gait Posture* 2012;36(1):7-15.
- (6) Coventry E, O'Connor KM, Hart BA, Earl JE, Ebersole KT. The effect of lower extremity fatigue on shock attenuation during single-leg landing. *Clin Biomech (Bristol , Avon)* 2006;21(10):1090-1097.
- (7) Delahunt E, Monaghan K, Caulfield B. Altered neuromuscular control and ankle joint kinematics during walking in subjects with functional instability of the ankle joint. *Am J Sports Med* 2006;34(12):1970-1976.
- (8) Delahunt E, Monaghan K, Caulfield B. Changes in lower limb kinematics, kinetics, and muscle activity in subjects with functional instability of the ankle joint during a single leg drop jump. *J Orthop Res* 2006;24(10):1991-2000.
- (9) Delahunt E, Monaghan K, Caulfield B. Ankle function during hopping in subjects with functional instability of the ankle joint. *Scand J Med Sci Sports* 2007;17(6):641-648.
- (10) Doherty C, Delahunt E, Caulfield B, Hertel J, Ryan J, Bleakley C. The Incidence and Prevalence of Ankle Sprain Injury: A Systematic Review and Meta-Analysis of Prospective Epidemiological Studies. *Sports Med* 2013.
- (11) Drewes LK, McKeon PO, Paolini G et al. Altered ankle kinematics and shank-rear-foot coupling in those with chronic ankle instability. *J Sport Rehabil* 2009;18(3):375-388.
- (12) Friston K, Ashburner J, Kiebel S, et al., Eds. *Statistical Parametric Mapping: The Analysis of Functional Brain Images*. London, United Kingdom: Elsevier; 2011, 656 pp.
- (13) Friston KJ, Holmes AP, Poline JB et al. Analysis of fMRI time-series revisited. *Neuroimage* 1995;2(1):45-53.
- (14) Gehring D, Wissler S, Mornieux G, Gollhofer A. How to sprain your ankle - a biomechanical case report of an inversion trauma. *J Biomech* 2013;46(1):175-178.
- (15) Gribble P, Robinson R. Differences in spatiotemporal landing variables during a dynamic stability task in subjects with CAI. *Scand J Med Sci Sports* 2010;20(1):e63-e71.
- (16) Gribble PA, Delahunt E, Bleakley C et al. Selection criteria for patients with chronic ankle instability in controlled research: a position statement of the international ankle consortium. *J Orthop Sports Phys Ther* 2013;43(8):585-591.
- (17) Gribble PA, Hertel J, Denegar CR. Chronic ankle instability and fatigue create proximal joint alterations during performance of the Star Excursion Balance Test. *Int J Sports Med* 2007;28(3):236-242.

- (18) Gribble PA, Robinson RH. Alterations in knee kinematics and dynamic stability associated with chronic ankle instability. *J Athl Train* 2009;44(4):350-355.
- (19) Hass CJ, Bishop MD, Doidge D, Wikstrom EA. Chronic ankle instability alters central organization of movement. *Am J Sports Med* 2010;38(4):829-834.
- (20) Hertel J. Functional Anatomy, Pathomechanics, and Pathophysiology of Lateral Ankle Instability. *J Athl Train* 2002;37(4):364-375.
- (21) Hertel J. Sensorimotor deficits with ankle sprains and chronic ankle instability. *Clin Sports Med* 2008;27(3):353-70, vii.
- (22) Imabayashi E, Matsuda H, Tabira T et al. Comparison between brain CT and MRI for voxel-based morphometry of Alzheimer's disease. *Brain Behav* 2013;3(4):487-493.
- (23) Kipp K, Palmieri-Smith RM. Principal component based analysis of biomechanical inter-trial variability in individuals with chronic ankle instability. *Clin Biomech (Bristol , Avon)* 2012;27(7):706-710.
- (24) Kipp K, Palmieri-Smith RM. Differences in kinematic control of ankle joint motions in people with chronic ankle instability. *Clin Biomech (Bristol , Avon)* 2013.
- (25) Konradsen L, Bech L, Ehrenbjerg M, Nickelsen T. Seven years follow-up after ankle inversion trauma. *Scand J Med Sci Sports* 2002;12(3):129-135.
- (26) Lin CF, Chen CY, Lin CW. Dynamic ankle control in athletes with ankle instability during sports maneuvers. *Am J Sports Med* 2011;39(9):2007-2015.
- (27) Monaghan K, Delahunt E, Caulfield B. Ankle function during gait in patients with chronic ankle instability compared to controls. *Clin Biomech (Bristol , Avon)* 2006;21(2):168-174.
- (28) Monteleone BJ, Ronsky JL, Meeuwisse WH, Zernicke RF. Ankle Kinematics and Muscle Activity in Functional Ankle Instability. *Clin J Sport Med* 2013.
- (29) Pataky TC. Generalized n-dimensional biomechanical field analysis using statistical parametric mapping. *J Biomech* 2010;43(10):1976-1982.
- (30) Pataky TC, Robinson MA, Vanrenterghem J. Vector field statistical analysis of kinematic and force trajectories. *J Biomech* 2013;46(14):2394-2401.
- (31) Robinson MA, Vanrenterghem J. An evaluation of anatomical and functional knee axis definition in the context of side-cutting. *J Biomech* 2012;45(11):1941-1946.
- (32) Sarma MK, Nagarajan R, Keller MA et al. Regional brain gray and white matter changes in perinatally HIV-infected adolescents. *Neuroimage Clin* 2013;4:29-34.
- (33) Schwartz MH, Rozumalski A. A new method for estimating joint parameters from motion data. *J Biomech* 2005;38(1):107-116.
- (34) Sell TC. An examination, correlation, and comparison of static and dynamic measures of postural stability in healthy, physically active adults. *Phys Ther Sport* 2012;13(2):80-86.
- (35) Valderrabano V, Frigg A, Leumann A, Horisberger M. [Total ankle arthroplasty in valgus ankle osteoarthritis]. *Orthopade* 2011;40(11):971-977.
- (36) Vanrenterghem J, Gormley D, Robinson M, Lees A. Solutions for representing the whole-body centre of mass in side cutting manoeuvres based on data that is typically available for lower limb kinematics. *Gait Posture* 2010;31(4):517-521.

- (37) Verrelst R, De Clercq D, Vanrenterghem J, Willems T, Palmans T, Witvrouw E. The role of proximal dynamic joint stability in the development of exertional medial tibial pain: a prospective study. *Br J Sports Med* 2014;48(5):388-393.
- (38) Wikstrom EA, Tillman MD, Schenker S, Borsa PA. Failed jump landing trials: deficits in neuromuscular control. *Scand J Med Sci Sports* 2008;18(1):55-61.
- (39) Wu G, Siegler S, Allard P et al. ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion--part I: ankle, hip, and spine. *International Society of Biomechanics. J Biomech* 2002;35(4):543-548.
- (40) Zhang SN, Bates BT, Dufek JS. Contributions of lower extremity joints to energy dissipation during landings. *Med Sci Sports Exerc* 2000;32(4):812-819.

Gait kinematics of subjects with ankle instability using a multi-segmented foot model

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Abstract

Objective: Many patients who sustain an acute lateral ankle sprain develop chronic ankle instability (CAI). Altered ankle kinematics have been reported to play a role in the underlying mechanisms of CAI. In previous studies, however, the foot was modeled as one rigid segment, ignoring the complexity of the ankle and foot anatomy and kinematics. The purpose of this study was to evaluate stance phase kinematics of subjects with CAI, copers, and controls during walking and running, using both a rigid and a multi-segmented foot model.

Methods: Foot and ankle kinematics of 77 subjects (29 subjects with self-reported CAI, 24 copers and 24 controls) were measured during barefoot walking and running, using a rigid foot model and the six-segment Ghent Foot Model. Data were collected on a 20m long instrumented runway embedded with a force plate and a 6-camera opto-electronic system. Groups were compared using Statistical Parametric Mapping.

Results: Both the CAI and the coper group showed similar differences during mid- and late stance compared to the control group ($p < 0.05$). The rigid foot segment showed a more everted position during walking compared to the control group. Based on the Ghent Foot Model, the rearfoot also showed a more everted position during running. The medial forefoot showed a more inverted position for both running and walking compared to the control group.

Conclusion: Our study revealed significant mid- and late stance differences in rigid foot, rearfoot and medial forefoot kinematics. The multi-segmented foot model demonstrated intricate behavior of the foot which is not detectable with rigid foot modeling. Further research using these models is necessary to expand knowledge of foot kinematics in subjects with CAI.

Introduction

An acute lateral ankle sprain is one of the most common sport-related injuries¹⁶, with many patients subsequently complaining of residual symptoms. According to a systematic review, 25% of all patients still experience pain and up to 34% report at least one re-sprain, 3 years after the initial sprain. In addition, up to 33%-53% of patients who sustained an acute ankle sprain develop a residual condition called chronic ankle instability (CAI).³⁶ CAI has been defined as the repetitive occurrence of instability, resulting in numerous ankle sprains.¹⁴ The instability is characterized by the subjective feeling of the ankle 'giving way' which refers to "the regular occurrence of uncontrolled and unpredictable episodes of excessive inversion of the rear foot, which do not result in an acute lateral ankle sprain".⁷ This condition has an impact on sport participation possibly leading to a lower level of performance or even a change of sport.^{1, 20} Furthermore, recurrent lateral ankle sprains are the primary cause of ligamentous posttraumatic ankle osteoarthritis.³⁴ Therefore, understanding the underlying mechanisms contributing to CAI is crucial for prevention and treatment purposes.

Altered kinematics of the ankle joint during walking and running have been reported to play a role in the underlying mechanisms of CAI. During walking, a more inverted position of the foot in the frontal plane has been found before, at, and immediately after heel strike and even throughout the whole gait cycle in patients with CAI.^{8, 24} For running conditions, a more inverted position of the ankle has been found only in the pre-landing phase²², along with a limited dorsiflexion range of motion at the ankle joint during the stance phase.¹⁰ Drewes et al.¹¹ showed more rearfoot inversion, however, throughout the whole gait cycle of jogging in patients with CAI. Furthermore, when comparing different instability groups and subjects with a history of an ankle sprain without CAI symptoms, no significant differences were shown in joint angle at initial contact and maximum displacement during stance phase for both walking and running.³ Despite some conflicting evidence, altered kinematics may very well contribute to CAI.

In previously reported research on contributing mechanisms for CAI only a small number of studies addressed ankle kinematics during gait. Hence, making a general statement on CAI-related ankle kinematic adaptations difficult. Moreover, in previous studies the foot was modeled as one rigid segment, thus ignoring the complexity of the ankle and foot anatomy and kinematics. Insight into foot function can be enhanced by the use of multi-segmented foot models³⁰ which have proved useful in other patient populations, e.g. diabetic foot patients³² and patients with rheumatoid arthritis⁴⁰. This approach may show kinematic patterns that a rigid foot would mask. Various studies have stated that

foot characteristics may play a role in the mechanism of an ankle sprain, e.g. a higher mobility of the first ray or medial arch height.^{23, 39} These findings call for more insight, not only into rearfoot kinematics, but also into the behavior of other foot segments during loading situations. At this moment, to the authors' knowledge, no research has been conducted in patients with CAI using a multi-segmented foot model.

Notwithstanding the relative high amount of patients who develop residual symptoms or chronic ankle instability after an acute ankle sprain, some patients return to their preinjury level of functional participation without any negative impact following a sustained sprain. These 'copers' somehow differ from subjects with CAI and identifying these differences might help clarify the contributing mechanisms to CAI. Other studies already identified some dissimilarities between subjects with CAI, copers and healthy controls, but further research is warranted.^{3, 37}

The purpose of this study was primarily to compare ankle and foot kinematics during the stance phase of gait between healthy controls and subjects with CAI, using both a rigid foot segment and the Ghent Foot Model⁵, a validated multi-segmented foot model. In addition, a third group of subjects with a recent ankle sprain, but without symptoms of CAI (copers), were included to evaluate possible kinematic adaptations and differences compared to the other groups. The rigid foot in this study was used to compare with literature and, in accordance with previous studies, a more inverted foot position and dorsiflexion reduction in subjects with CAI was hypothesized.

Methods

Subjects

Twenty-nine subjects with CAI (15 males and 14 females, 10±13 sprains annually, 5±3months to last sprain), 24 subjects with a recent ankle sprain (12 males and 12 females, 12±5 months to last sprain) and 24 controls (10 males and 14 females) participated in this study. For the CAI group, all of the following inclusion criteria had to be met: (1) a history of at least one ankle sprain which resulted in pain, swelling, and stiffness prohibiting participation in sport-, recreational or other activities for at least 3 weeks; (2) repeated ankle sprains; (3) presence of giving way; (4) feeling of weakness round the ankle, and (5) a decreased functional participation (recreational, competitive or professionally) as a result of the ankle sprains. The control group had no history of lower leg injury in the last two years. The third group, the copers, consisted of subjects who had sustained an ankle sprain in the last two years, but were not suffering from ankle instability, as defined above (criteria 2 to 5 were exclusion criteria). Overall

exclusion criteria were ankle fracture or surgery, lower limb pain (not related to an ankle sprain), an ankle sprain in the last 3 months and equilibrium deficits. All subjects were recreationally active, defined by at least 1.5 hours of cardiovascular activity per week. Subject characteristics are shown in table 1. The Ghent University Hospital ethics committee approved this study and all subjects provided informed consent before participation.

Table 1: Group mean (SD) for demographic variables.

	CAI (n=29)	COP (n=24)	CON (n=24)
Age (yrs)	21.9 (3.3)*	20.3 (1.9)*	25.8 (1.9)*
Height (cm)	175.8 (9.8)	178.2 (9.2)	173.0 (8.9)
Weight (kg)	71.0 (13.4)	69.8 (7.38)	65.9 (9.2)
BMI	22.9 (3.6)	22.0 (1.6)	21.9 (1.8)
FADI	86.3 (9.9) [†]	98.9 (2.4) [†]	100 (0.0) [†]
FADI-S	70.5 (11.5) [‡]	95.9 (4.5) [‡]	100 (0.0) [‡]

Differences between groups are non-significant ($p>0.05$) except for age* ($p<0.001$) for control in comparison with both coper and CAI. FADI[†] (Functional Ankle Disability Index) and FADI-S[‡] (Functional Ankle Disability Index-Sport subscale) score were significantly lower in the CAI group compared to both the coper and control group ($p<0.001$).

Instruments

Kinematic data were collected at 500 Hz on a 20m long instrumented runway with a 6 camera opto-electronic system (OQUS 3, Qualysis). A force plate (AMTI, 500Hz) was built into the runway for synchronized event detection. In addition, a normal video camera (Sony, 25Hz) captured the test trials for a visual control record.

Experimental procedure

For each subject, anthropometric characteristics were registered and a questionnaire about the medical history was completed. Subjects also filled out the Foot and Ankle Disability Index (FADI) and its sport subscale (FADI-S) for baseline functionality assessment. The results of this assessment were not used as inclusion criteria, but as a discriminative measure between groups (table 1). Subjects were tested unilaterally. The most unstable ankle, based on the subject's medical history, was analyzed in the CAI group. In the coper group, the side was selected depending on which ankle the subject had sprained in the last 2 years. If the subject had sprained both ankles in the last 2 years, the most recently sprained ankle was included in the study. In the control group the foot chosen was randomized. Chi-square tests

showed that there was no significant difference in the amount of dominant versus non-dominant tested ankles between groups.

For capturing kinematic data, spherical reflective surface markers (7mm) were placed using double-sided tape on anatomical landmarks of the foot and lower leg, along with tracking markers, according to the Ghent Foot Model⁵. This six-segment model is defined by the shank, rear foot, midfoot, medial and lateral forefoot, and the hallux (figure 1). Markers were placed by the same researcher for all subjects. First a static measurement was recorded for 5 seconds to define the different segments of the GFM. During this measurement, the subject had to perform a tandem stand with the tested leg in front and the front knee slightly flexed so that the lower leg was perpendicular to the floor.

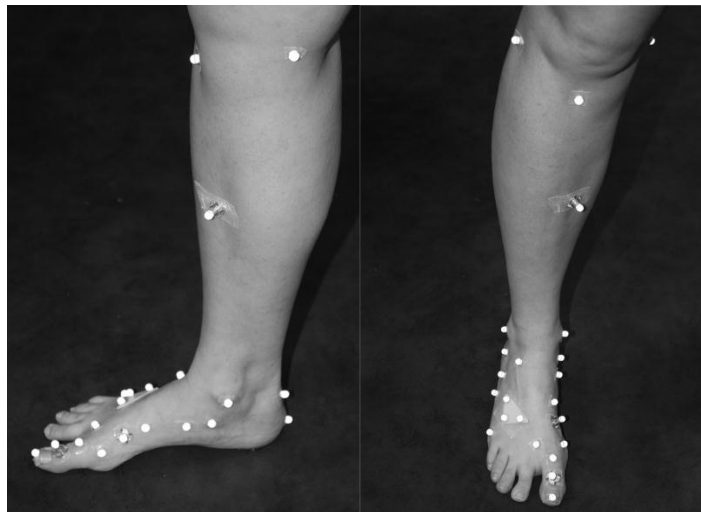


Figure 1. Marker locations according to the Ghent Foot Model.

During the gait measurements, speed was monitored using a walk and jog laser (Astech LDM 42A, 50Hz), which was pointed at the subject's thorax. Subjects had to walk barefoot at a constant speed of 1.5m/s (1.4-1.6m/s) while data was collected using a mid-gait protocol. During running, subjects had to maintain a constant speed of 3.5m/s (3.3-3.7m/s). The starting position for running was 10 meters before the force plate. Subjects were first allowed to familiarize themselves with the test procedure by performing a minimum of 3 practice trials. The actual test was repeated until 3 usable trials were captured. Trials were discarded if the speed was not in range, if two feet touched the force plate, or if subjects were seen to show an adaptation in stride length or frequency in an attempt to hit the force plate.

Data analysis

Kinematic data were processed by using Visual 3D (C-motion, Germantown, MD). The dependent variables calculated for this study, were the joint angles of the rigid foot and the different segments of the GFM. Before joint angle calculation, marker coordinates were filtered using a fourth order Butterworth low-pass filter at 10 Hz for walking and at 15 Hz for running, with 50 points reflected. Inter-joint motion was calculated using Euler rotations (X-Y-Z).⁵ Rotation around the X-, Y- and Z-axis defined respectively the plantar-/dorsiflexion (sagittal plane), in-/ eversion (frontal plane) and ab-/adduction (transversal plane) motion. The stance phase was determined using the vertical component of the ground reaction force with a threshold set at 10 N, and then each point in the time series was normalized to 100%. The rigid foot was defined by markers on the calcaneus, the lateral malleolus, and the head of the first and fifth metatarsal heads. The other segments were defined according to the multi-segmented GFM.⁵ For each subject, the three trials per condition were averaged.

To compare between groups, a curve analysis was performed using statistical parametric mapping (SPM).¹³ Initially, ANOVA over the normalized time series was used to establish the presence of any significant differences between the three groups. If statistical significance was reached, post-hoc t-tests over the normalized time series were used to determine between which groups significant differences occurred. For both the ANOVA and t-test analyses, SPM involved four steps. The first was computing the value of a test statistic at each point in the normalized time series. The second was estimating temporal smoothness based on the average temporal gradient. The third was computing the value of test statistic above which only alpha=5% of the data would be expected to reach had the test statistic trajectory resulted from an equally smooth random process. The last was computing the probability that specific supra-threshold regions could have resulted from an equivalently smooth random process. Technical details are provided elsewhere.^{13, 27}

Results

Curve analyses

Overall, rotations in the frontal plane representing inversion/eversion showed significant ANOVA results ($p < 0.05$) for the rigid foot, the rearfoot, midfoot, and the medial forefoot during mid- and late stance. Furthermore, ANOVA results ($p < 0.05$) indicated differences in rotations in the sagittal and transversal plane for the rearfoot during walking. Post-hoc analysis results are presented below and showed similar

findings for both the CAI and coper group compared to the control group. No differences were found for plantar/dorsiflexion and abduction/adduction angles for both running and walking data in the post-hoc analysis.

Foot (rigid foot in relation to the shank): Walking analysis showed a significantly greater eversion angle in the CAI group from 11-73% of the stance phase (average difference of 2.17° , $p < 0.001$), and in the coper group from 19-73%, compared to the control group (average difference of 2.19° , $p < 0.001$). During the significant period of this midstance phase, the foot first progressed towards a maximally everted position and then subsequently inverted towards the end of this phase (figure 2). No significant differences were found for the running data.

Rearfoot (in relation to the shank): The running trials exhibited a significantly greater eversion of the rearfoot in the CAI group from 56-73% of the stance phase (average difference of 2.72° , $p = 0.045$), and in the COP group from 29-86% (average difference of 3.47° , $p = 0.001$), compared to controls. The rearfoot reached a maximally everted position in the beginning of the midstance, and then slowly supinated, during the period with significant differences, towards toe off (figure 3). No significant differences were found for the walking data.

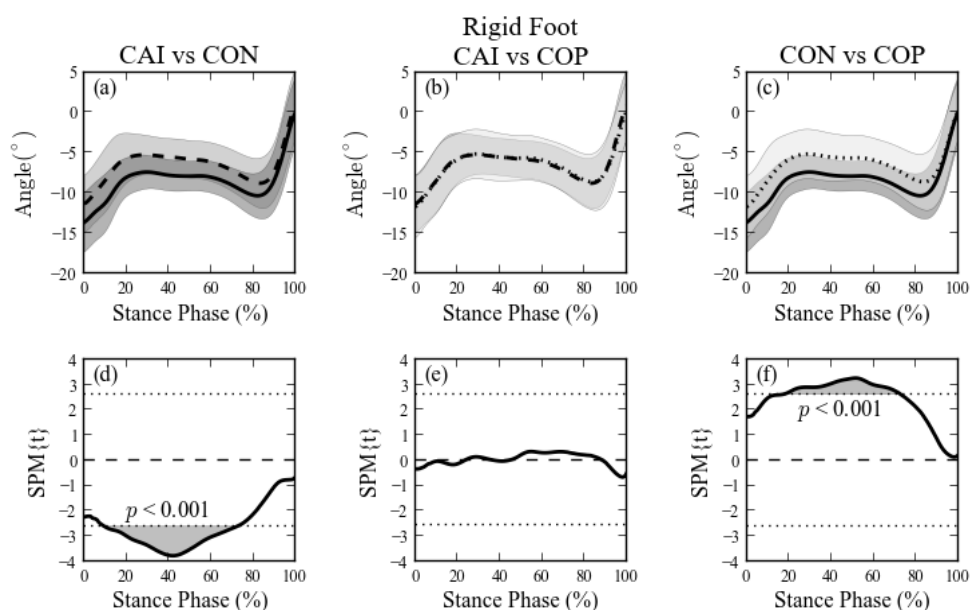


Figure 2. Kinematic between-group comparison of the rigid foot during walking (CAI =dashed --; COP =dotted .; CON =solid _). (a,b,c) Mean ankle joint kinematic trajectories with standard deviation clouds. (d,e,f) Statistical Parametric Mapping results; "SPM{t}" is the trajectory Student's t statistic or, equivalently, the mean difference curve normalised by sample-size normalised variance. The dotted horizontal line indicates the random field theory threshold for significance, and p values indicate the likelihood that a random process of the same temporal smoothness would be expected to produce a supra-threshold cluster of the observed size.

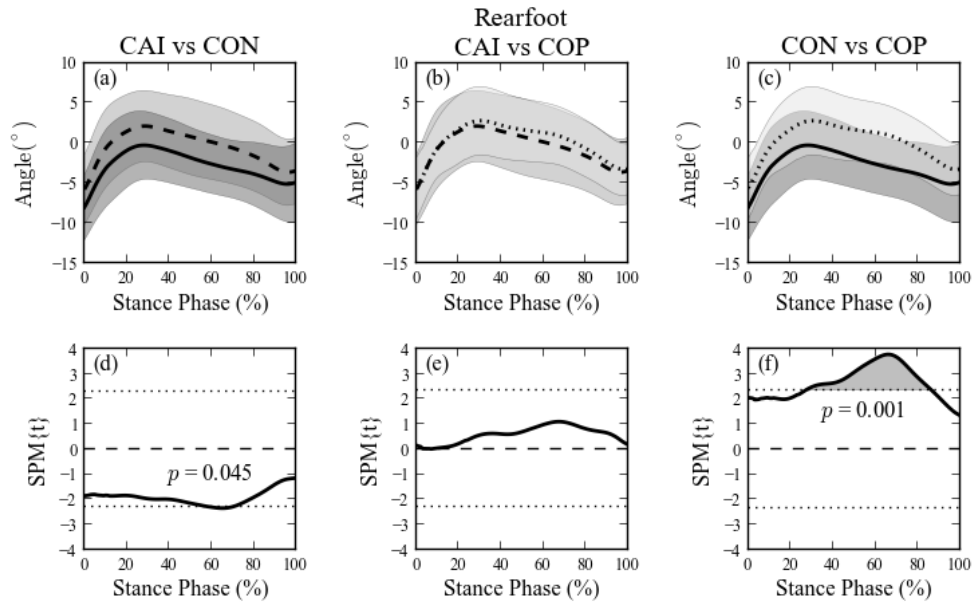


Figure 3. Kinematic between-group comparison (a,b,c) of the rearfoot during running (CAI =dashed --; COP =dotted ...; CON =solid ___) with statistical parametric mapping analysis underneath (d,e,f). SPM{t} is the trajectory of the Student's t statistic.

Midfoot (in relation to the rearfoot): No significant between-group differences for walking and running trials were found.

Lateral forefoot (in relation to the midfoot): No significant between-group differences for walking and running trials were found.

Medial forefoot (in relation to the midfoot): For both walking and running, the CAI group showed significantly more inversion compared to the control group from 87-98% of stance phase (average difference of 9.42° , $p=0.031$) during walking and from 56-91% (average difference of 9.81° , $p<0.001$), during running. During this significant period, the medial forefoot everted until maximal before supinating at the end of stance phase. The coper group showed significantly more inversion compared to the control group from 10-83% of the stance phase in walking (average difference of 7.42° , $p=0.007$) and from 28-30% of the stance phase in running (average difference of 8.28° , $p=0.049$) (figure 4 and 5). The medial forefoot first supinated to a maximally supinated position in this period, and then started to evert towards the end of midstance (only significant for the walking condition).

Hallux (medial forefoot-hallux): No significant between-group differences for walking and running trials were found.

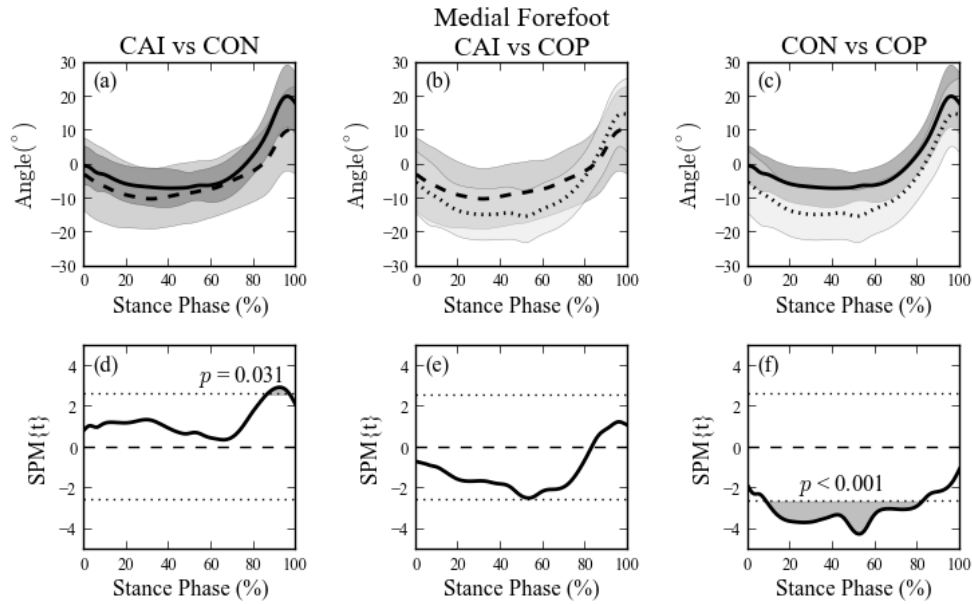


Figure 4. Kinematic between-group comparison (a,b,c) of the medial forefoot during walking (CAI =dashed --; COP =dotted ...; CON =solid __) with statistical parametric mapping analysis underneath (d,e,f). SPM{t} is the trajectory of the Student's t statistic.

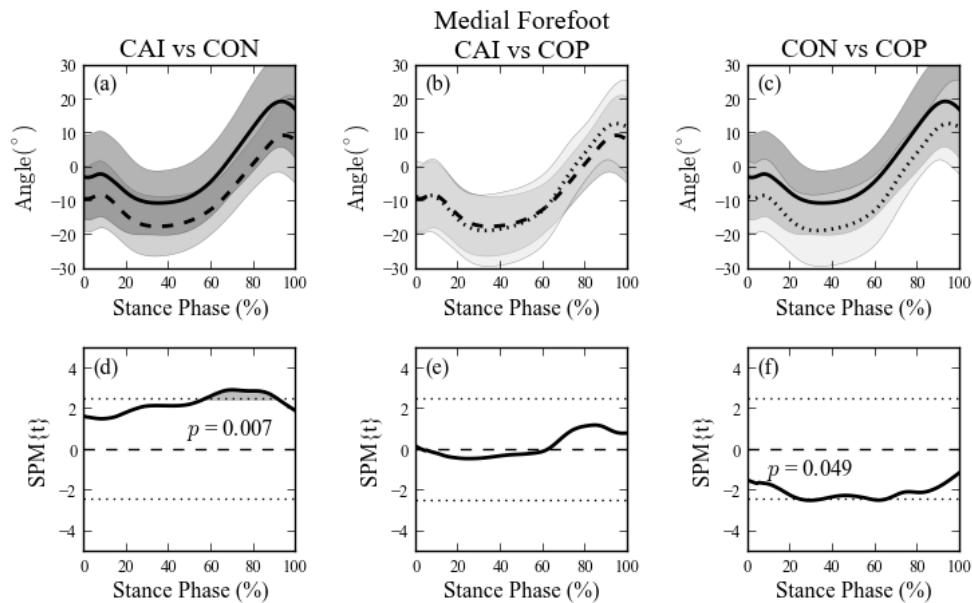


Figure 5. Kinematic between-group comparison (a,b,c) of the medial forefoot during running (CAI =dashed --; COP =dotted ...; CON =solid __) with statistical parametric mapping analysis underneath (d,e,f). SPM{t} is the trajectory of the Student's t statistic.

Discussion

To our knowledge, this was the first study that used a multi-segmented foot model to describe gait kinematics in subjects with CAI. The aim was to explore kinematic differences based on the rigid foot and Ghent Foot Model⁵ between the three study groups. Moreover, statistical parametric mapping allowed us to compare groups throughout the entire stance phase, alleviating a-priori assumptions about when in the stance phase statistical differences might occur.²⁷ In general, similar differences were found between the CAI and copers group compared to the control group. Our results show no significant kinematic differences in the early stance phase, which was not expected based on literature.^{8, 22, 24} We did identify differences in the mid- and late stance, which could possibly be linked to the mechanism of CAI.

Ankle kinematics based on the rigid foot model indicated a more everted foot for both the CAI and the copers group, compared to the control group. The difference was significant from approximately 10% and 20%, respectively, to 70% of stance during walking, with no significant difference for the remainder of stance. Our results deviate from findings in literature indicating a more inverted foot position at and just after heel strike^{8, 24} or during the whole stance phase¹¹. In the study of Delahunt et al.⁸, a more inverted foot position was also found before heel strike. However, our study only analysed the stance phase and disregarded the swing phase of the gait cycle. Previous data on kinematics throughout the entire stance phase to compare results to is scarce. The more everted position of the foot in subjects with a history of ankle sprains found in our study, does not seem to fit, with the pathomechanics of an ankle sprain. Nevertheless, a prospective study by Willems et al.³⁸ on gait related risk factors for ankle sprains found an increased medial loading of the foot and a trend of higher eversion excursion in subjects susceptible for an ankle sprain. They suggested that an unstable feeling might result in a more medial foot roll-off as a compensation for possible ankle sprains. This compensation mechanism might also cause the higher foot eversion found in the current study. A recent study on evector and invertor muscle strength in patients with CAI might provide an alternative hypothesis on the more everted foot position.⁴ These authors found an overall decrease in muscle strength and a significantly higher concentric evector to eccentric invertor torque ratio in subject with CAI. This imbalanced ratio may result in an inadequate eccentric control of eversion during gait. In comparison, a study by Rabbito et al.²⁹ found a greater eversion during walking related to a posterior tibial tendon dysfunction. These results might also explain the more everted foot position found here, but further research is necessary to be able to identify the precise underlying mechanism. Furthermore, our results

showed, no decreased dorsiflexion for the CAI group during stance phase (cf. Drewes et al., 2009). In general, for the rigid foot kinematics, the current study does not confirm the postulated hypotheses of more inversion and dorsiflexion in gait in subjects with CAI.

In their review on foot characteristics in relation to ankle sprains, Morisson and Kaminski²⁵ emphasized the possible midfoot and forefoot involvement. They underlined the importance of capturing foot motion to be able to understand lower extremity mechanics and foot-related risk factors for a lateral ankle sprain. In the past, studies using static measurements, have identified e.g. a lower medial arch and a greater metatarsophalangeal joint extension as possible risk factors for a lateral ankle sprain.^{23, 39} However, to date, no kinematic evaluation has been made using a multi-segmented model to compare motions at mid and forefoot joints during a functional movement in ankle sprainers. In our study, multi-segmented ankle and foot kinematics based on GFM demonstrated several between-group differences. The rearfoot was more everted during midstance of running for both the CAI and copers group in comparison to the control group. In addition, the medial forefoot defined by the first ray showed a more inverted position in mid- and late stance for both walking and running. A possible explanation for this phenomenon may be found in the function of the peroneus longus (PL), which everts the first ray during the stance phase of gait. The PL is also believed to exert a stabilizing influence on the first ray.¹⁹ Since in this study a more inverted first ray is found in subjects with CAI, we assume the normal function of PL could be impaired in these subjects which is in line with the study of Santilli et al.³¹ who found a decreased activity of the PL during stance phase in subjects with functional instability. Furthermore, the PL is found to be active in mid- and late stance of a gait cycle¹⁸, which corresponds with the timing of the observed kinematic differences for the medial forefoot. In addition, another possible explanation might be found in the biomechanical coupling of rear- and forefoot motion, where a pronation motion of the rearfoot, as seen here, is associated with a supination motion of the forefoot to be able to maintain full ground contact.³⁵ This inverted position of the first ray results in a so-called loose-packed position which reflects a mechanically less stable condition.²⁸ Plantar pressure data also indicated a more laterally deviated pressure displacement in forefoot during the late stance phase as a risk factor for ankle sprains phase.³⁸ Maybe the less stable position of the first ray, found in this study, might explain these plantar pressure results. Therefore, medial forefoot kinematics may play a role in the mechanism of CAI.

The results of this study indicated differences in the mid- and late stance phase of a gait cycle and not in the initial post impact phase after heel strike. This might not be expected, as it is generally considered that ankle sprains occur in the initial loading response phase. However, the exact timing of

the ankle sprain mechanism in a heel to toe foot roll-off during gait conditions, based on real ankle sprain events, has not been determined yet, due to ethical considerations. Some authors have pointed out that other possible time frames might also be important during a gait cycle. Stormont et al.³³ indicated that ankle instability may occur during both loading and unloading transitions. Furthermore, Konradsen and Voigt²¹ demonstrated, based on a cadaver study, that the ankle and foot will be able to stabilize itself and move into normal eversion at the beginning of the stance phase even though it is set to the ground with a substantial degree of malalignment. They therefore concluded that sustaining an ankle sprain due to pre-impact unintentional malalignment of the ankle seems improbable.²¹ Other studies on plantar pressure data also indicated deviations during midstance in relation to chronic ankle instability²⁶ and late stance as a risk factor for ankle sprains.³⁸ The mid- and late stance findings in our study contribute to the concept of other possible important time frames in the mechanism of ankle injuries during gait. Moreover, findings in these timeframes may very well be relevant in view of the fact that a lot of ankle sprains happen during jump landing activities in which the forefoot is the first part of the foot to touch the ground surface in a toe to heel foot roll-off. Further research on multi-segmented landing kinematics is therefore warranted.

In this study, three different groups were defined. For the instability group, only subjects with functional ankle instability were selected based on the described inclusion criteria. For the copers group, subjects with a recent ankle sprain were chosen because, they are more susceptible for resprain.¹⁷ For some reason these subjects had not developed a chronic condition as of yet and therefore were interesting to consider as a separate group. It is therefore noteworthy that no kinematic differences were found between the CAI group and the copers group. This means that our copers group had the same kinematic adaptations after sustaining a recent ankle sprain as the group with a chronically unstable ankle. The FADI and FADI-S on the contrary clearly discriminated between these groups regarding subjective ankle complaints.¹² A possible explanation may be found in other influencing factors such as proprioception, postural stability, strength or neuromuscular control.^{15, 17} Further research is necessary to elucidate the underlying differentiating mechanisms that define a copers and that differentiate between copers and subjects with CAI.

Although we feel that the results of the present study are promising, there are some methodological limitations to bear in mind. Both walking and running occurred barefooted. Mechanical differences have been demonstrated between barefoot and shod locomotion⁹, in particular, increased ankle plantar flexion and reduced eversion were reported in barefoot running compared to shod running.⁶ Although barefoot running may not be completely representative for normal shod conditions, alternatives are not

always obvious when using a multi-segmented model. Group definitions used in this study may differ from other studies making comparison difficult. The copers group used in our study had to have had a relatively recent ankle sprain. Other studies have used the term copers for everyone who ever sprained their ankle, but who did not develop CAI.^{2, 3} However, possible coping strategies in the acute phase may not be present or may be different several years after sustaining an ankle sprain. Moreover, kinematics of someone who sprained their ankle some years ago may not be representative for their kinematics at that moment in time. Therefore, we chose copers with a recent sprain for our study. For data collection, we only looked at the stance phase and, therefore, maybe missed important information on approach kinematics.^{8, 22, 24} This was due to a technical limitation of our capturing volume and should be further addressed in future research. Furthermore, we did not normalize data against a reference value, so not to eliminate inherent variations in foot morphology from our data. One might possibly argue that foot morphology may differ between groups and should be excluded from actual kinematics. Future research should also address multi-segment foot kinematics in more provocative situations, such as drop landings or sidestepping maneuvers, which may also show altered foot and ankle kinematics in subjects with CAI.

Conclusion

This study indicates possible benefits of using a multi-segmented foot model in the search for contributing factors in the mechanism of chronic ankle instability during the stance phase of gait. During midstance, we found a more everted position of the rigid foot during walking and of the rearfoot during running. In addition, we found a more inverted position for the medial forefoot in both the CAI and copers group compared to the control group during mid- and late stance, possibly reflecting a mechanically less stable position. These results warrant further research to expand the knowledge regarding foot kinematics in subjects with CAI.

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References

- (1) Anandacoomarasamy A, Barnsley L. Long term outcomes of inversion ankle injuries. *Br J Sports Med* 2005;39(3):e14.
- (2) Brown C. Foot clearance in walking and running in individuals with ankle instability. *Am J Sports Med* 2011;39(8):1769-1776.
- (3) Brown C, Padua D, Marshall SW, Guskiewicz K. Individuals with mechanical ankle instability exhibit different motion patterns than those with functional ankle instability and ankle sprain copers. *Clin Biomech (Bristol, Avon)* 2008;23(6):822-831.
- (4) David P, Halimi M, Mora I, Doutrelot PL, Petitjean M. Isokinetic Testing of Evertor and Invertor Muscles in Patients with Chronic Ankle Instability. *J Appl Biomech* 2013.
- (5) De Mits S, Segers V, Woodburn J, Elewaut D, De Clercq D, Roosen P. A clinically applicable six-segmented foot model. *J Orthop Res* 2011.
- (6) De Wit B, De Clercq D, Aerts P. Biomechanical analysis of the stance phase during barefoot and shod running. *J Biomech* 2000;33(3):269-278.
- (7) Delahunt E, Coughlan GF, Caulfield B, Nightingale EJ, Lin CW, Hiller CE. Inclusion criteria when investigating insufficiencies in chronic ankle instability. *Med Sci Sports Exerc* 2010;42(11):2106-2121.
- (8) Delahunt E, Monaghan K, Caulfield B. Altered neuromuscular control and ankle joint kinematics during walking in subjects with functional instability of the ankle joint. *Am J Sports Med* 2006;34(12):1970-1976.
- (9) Divert C, Mornieux G, Baur H, Mayer F, Belli A. Mechanical comparison of barefoot and shod running. *Int J Sports Med* 2005;26(7):593-598.
- (10) Drewes LK, McKeon PO, Kerrigan DC, Hertel J. Dorsiflexion deficit during jogging with chronic ankle instability. *J Sci Med Sport* 2009;12(6):685-687.
- (11) Drewes LK, McKeon PO, Paolini G et al. Altered ankle kinematics and shank-rear-foot coupling in those with chronic ankle instability. *J Sport Rehabil* 2009;18(3):375-388.
- (12) Eechaute C, Vaes P, Van AL, Asman S, Duquet W. The clinimetric qualities of patient-assessed instruments for measuring chronic ankle instability: a systematic review. *BMC Musculoskelet Disord* 2007;8:6.
- (13) Friston, K, Ashburner J, Kiebel S, et al., Eds. *Statistical Parametric Mapping: The Analysis of Functional Brain Images*. London, United Kingdom: Elsevier; 2011, 656 pp.
- (14) Hertel J. Functional Anatomy, Pathomechanics, and Pathophysiology of Lateral Ankle Instability. *J Athl Train* 2002;37(4):364-375.
- (15) Hiller CE, Nightingale EJ, Lin CW, Coughlan GF, Caulfield B, Delahunt E. Characteristics of people with recurrent ankle sprains: a systematic review with meta-analysis. *Br J Sports Med* 2011;45(8):660-672.
- (16) Hootman JM, Dick R, Agel J. Epidemiology of collegiate injuries for 15 sports: summary and recommendations for injury prevention initiatives. *J Athl Train* 2007;42(2):311-319.
- (17) Hubbard TJ, Kramer LC, Denegar CR, Hertel J. Contributing factors to chronic ankle instability. *Foot Ankle Int* 2007;28(3):343-354.
- (18) Hunt AE, Smith RM, Torode M. Extrinsic muscle activity, foot motion and ankle joint moments during the stance phase of walking. *Foot Ankle Int* 2001;22(1):31-41.
- (19) Johnson CH, Christensen JC. Biomechanics of the first ray. Part I. The effects of peroneus longus function: a three-dimensional kinematic study on a cadaver model. *J Foot Ankle Surg* 1999;38(5):313-321.

- (20) Konradsen L, Bech L, Ehrenbjerg M, Nickelsen T. Seven years follow-up after ankle inversion trauma. *Scand J Med Sci Sports* 2002;12(3):129-135.
- (21) Konradsen L, Voigt M. Inversion injury biomechanics in functional ankle instability: a cadaver study of simulated gait. *Scand J Med Sci Sports* 2002;12(6):329-336.
- (22) Lin CF, Chen CY, Lin CW. Dynamic ankle control in athletes with ankle instability during sports maneuvers. *Am J Sports Med* 2011;39(9):2007-2015.
- (23) Mei-Dan O, Kahn G, Zeev A et al. The medial longitudinal arch as a possible risk factor for ankle sprains: a prospective study in 83 female infantry recruits. *Foot Ankle Int* 2005;26(2):180-183.
- (24) Monaghan K, Delahunt E, Caulfield B. Ankle function during gait in patients with chronic ankle instability compared to controls. *Clin Biomech (Bristol, Avon)* 2006;21(2):168-174.
- (25) Morrison KE, Kaminski TW. Foot characteristics in association with inversion ankle injury. *J Athl Train* 2007;42(1):135-142.
- (26) Nawata K, Nishihara S, Hayashi I, Teshima R. Plantar pressure distribution during gait in athletes with functional instability of the ankle joint: preliminary report. *J Orthop Sci* 2005;10(3):298-301.
- (27) Pataky TC. Generalized n-dimensional biomechanical field analysis using statistical parametric mapping. *J Biomech* 2010;43(10):1976-1982.
- (28) Perez HR, Reber LK, Christensen JC. The effect of frontal plane position on first ray motion: forefoot locking mechanism. *Foot Ankle Int* 2008;29(1):72-76.
- (29) Rabbito M, Pohl MB, Humble N, Ferber R. Biomechanical and clinical factors related to stage I posterior tibial tendon dysfunction. *J Orthop Sports Phys Ther* 2011;41(10):776-784.
- (30) Rankine L, Long J, Canseco K, Harris GF. Multisegmental foot modeling: a review. *Crit Rev Biomed Eng* 2008;36(2-3):127-181.
- (31) Santilli V, Frascarelli MA, Paoloni M et al. Peroneus longus muscle activation pattern during gait cycle in athletes affected by functional ankle instability: a surface electromyographic study. *Am J Sports Med* 2005;33(8):1183-1187.
- (32) Sawacha Z, Cristoferi G, Guarneri G et al. Characterizing multisegment foot kinematics during gait in diabetic foot patients. *J Neuroeng Rehabil* 2009;6:37.
- (33) Stormont DM, Morrey BF, An KN, Cass JR. Stability of the loaded ankle. Relation between articular restraint and primary and secondary static restraints. *Am J Sports Med* 1985;13(5):295-300.
- (34) Valderrabano V, Hintermann B, Horisberger M, Fung TS. Ligamentous posttraumatic ankle osteoarthritis. *Am J Sports Med* 2006;34(4):612-620.
- (35) Valmassy R. *Clinical biomechanics of the lower extremities*. Mosby; 2012.p.19-21.
- (36) van Rijn RM, van Os AG, Bernsen RM, Luijsterburg PA, Koes BW, Bierma-Zeinstra SM. What is the clinical course of acute ankle sprains? A systematic literature review. *Am J Med* 2008;121(4):324-331.
- (37) Wikstrom EA, Tillman MD, Chmielewski TL, Cauraugh JH, Naugle KE, Borsa PA. Discriminating between copers and people with chronic ankle instability. *J Athl Train* 2012;47(2):136-142.
- (38) Willems T, Witvrouw E, Delbaere K, De CA, De CD. Relationship between gait biomechanics and inversion sprains: a prospective study of risk factors. *Gait Posture* 2005;21(4):379-387.
- (39) Willems TM, Witvrouw E, Delbaere K, Philippaerts R, De B, I, De CD. Intrinsic risk factors for inversion ankle sprains in females--a prospective study. *Scand J Med Sci Sports* 2005;15(5):336-345.
- (40) Woodburn J, Nelson KM, Siegel KL, Kepple TM, Gerber LH. Multisegment foot motion during gait: proof of concept in rheumatoid arthritis. *J Rheumatol* 2004;31(10):1918-1927.

**Multi-segmented foot landing kinematics in subjects
with chronic ankle instability.**

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Clinical biomechanics (under revision)

Abstract

Objective: Chronic ankle instability has been associated with inadequate control during landing tasks and altered joint kinematics at the ankle, knee and hip. However, no studies have investigated possible kinematical deflections at more distal segments of the foot. The purpose of this study was to evaluate if subjects with chronic ankle instability and copers show altered ankle and foot kinematics during a landing tasks compared to controls.

Methods: 96 subjects (38 subjects with chronic ankle instability, 28 copers and 30 controls) performed a vertical drop and side jump task, while foot and ankle kinematics were registered using the six-segment Ghent Foot Model and a rigid foot model. Group differences were evaluated using Statistical Parametric Mapping and analysis of variance.

Results: Overall, similar sagittal plane differences were found for vertical drop and side jump. Subjects with chronic ankle instability and copers exhibited less plantar flexion at touch down. In addition, the chronic ankle instability group demonstrated a stiffer landing pattern compared to the control group, leading to higher loading rates. Furthermore, subjects with chronic ankle instability had a more inverted midfoot position compared to controls during side jump and more midfoot inversion/eversion range of motion than copers during vertical drop. Copers exhibited less plantar flexion/dorsiflexion range of motion in the lateral and medial forefoot for both conditions.

Conclusion: Subjects with chronic ankle instability displayed an altered, stiffer kinematic landing strategy and related alterations in landing kinetics, which might predispose them for episodes of giving way and actual ankle sprain events.

Introduction

Ankle sprains are one of the most frequently observed sport injuries, representing between 10-30% of all registered musculoskeletal injuries.¹¹ In 80% of the cases it involves an inversion trauma with damage to the lateral ligaments.¹¹ In the United States, up to 27,000 ankle sprains occur daily.²³ As a consequence of sustaining an initial ankle sprain, many patients experience residual symptoms such as pain, swelling, and even re-sprains. Moreover, up to 53% of all patients report a residual complaint described as chronic ankle instability (CAI).²⁷ CAI has been defined as the repetitive occurrence of instability, resulting in numerous ankle sprains.¹⁵ In view of the high occurrence rate of CAI, the impact on the level of performance in sports participation^{1, 18}, and possible degenerative long term consequences²⁶, it is necessary for clinicians to gain a better understanding of the underlying mechanisms.

Ankle sprains often occur during activities which involve jumping, landing and turning, e.g. during sports such as basketball, volleyball and soccer.³¹ Inadequate joint control during landing tasks might be a key factor in this, with biomechanical research indicating that ankle joint kinematics can reveal detriments in the capacity to modify and control the high loading associated with landing tasks³². Differences in timing and magnitude of ground reaction forces (GRF) between subjects with CAI and controls have been reported.^{3, 8} In addition, research on landing kinematics in subjects with CAI revealed several kinematic differences not only at the level of the ankle, but also at more proximal joints, i.e. the knee and the hip.^{4, 8, 13} For the ankle joint, a more inverted position of the ankle has been shown during the postlanding phase of a stop-jump landing task¹⁹ and during the pre- and postlanding phase of lateral hop.⁹ Furthermore, a greater ankle dorsiflexion prior to and post landing in a single leg jump has been demonstrated.⁴ Notwithstanding some conflicting results, possibly caused by differences in landing tasks, observation of lower limb joint kinematics may well offer a window into the underlying mechanisms of CAI.

Although current research has focused on the kinematics at the ankle and more proximal joints in subjects with CAI, to the author's knowledge no studies have been done investigating kinematic adaptations during landing distal of the ankle, i.e. at the foot. In previous research on landing the foot was modeled as one rigid segment, ignoring the functional anatomy of the ankle-foot complex. However, mid- and forefoot characteristics have been acknowledged to possibly play a role in the mechanism of an ankle sprain.²⁰ In addition, rearfoot and medial forefoot kinematics have been shown to differ between subjects with CAI and healthy controls during gait.⁶ Insight in foot function during landing tasks could

therefore be enhanced by the use of multi-segmented foot models.²² Moreover, with first foot contact during landing happening on the forefoot, differences in foot segment kinematics may as well influence ankle kinematics and more proximal joints in the kinetic chain. Foot segment kinematics might also reveal impaired force dissipation strategies at touch down, potentially putting a subject with CAI at risk for re-spraining their ankle.

The main goal of this study was to identify differences in ankle and foot kinematics during the impact phase of a landing task in subjects with CAI compared to a control group. In addition, rigid foot kinematics were evaluated to compare results with existing literature. To even better understand the CAI mechanism, a copers group was included. The members of this group were defined as subjects who had not experienced negative effects following their rehabilitation from a sprain, and returned to their pre-injury sporting level. Foot segment kinematics were also observed against vertical ground reaction force (GRF) patterns to reveal whether force dissipation strategies were impaired in subjects with CAI.

Methods

Subjects

A total of 96 participants took part in this study (table 1). Thirty-eight subjects with CAI (19 males and 19 females, 5 (SD 3) months to last sprain, 10 (SD 13) sprains annually), 28 copers (14 males and 14 females, 11 (SD 5) months to last sprain) and 30 controls (12 males and 18 females) were recruited. All of the following inclusion criteria had to be met to be eligible for the CAI group: (1) a history of at least one ankle sprain which resulted in pain, swelling, and stiffness prohibiting participation in sport-, recreational or other activities for at least three weeks; (2) repeated ankle sprains; (3) presence of giving way; (4) feeling of weakness around the ankle, and (5) a decreased functional participation (recreational, competitive or professionally) as a result of the ankle sprains. The copers were defined as subjects with a history of an ankle sprain in the last two years, but who had no characteristics of chronic ankle instability. Subjects in the control group reported no lower leg injury in the past two years. Overall, all subjects had to perform at least 1.5 hours of cardiovascular activity per week. Exclusion criteria were a history of ankle fracture or surgery, lower limb pain at the moment of the test procedure, an ankle sprain in the last 3 months, and equilibrium deficits. The ethics committee approved this study and all subjects signed the informed consent.

Table 1: Group mean (SD) for demographic variables.

	CON (n=30)	COP (n=28)	CAI (n=38)
Age (yrs)	25.7 (1.8)*	20.3 (1.9)*	22.1 (3.4)*
Height (cm)	173.6 (9.4)	177.6 (10.2)	175.4 (8.3)
BMI	21.8 (1.8)	22.1 (1.7)	23.1 (3.4)
FADI	100 (0.0) [†]	99.0 (2.4) [†]	89.2 (7.2) [†]
FADI-S	100 (0.0) [‡]	96.2 (4.8) [‡]	72.7 (10.2) [‡]

Differences between groups are non-significant ($p>0.05$) except for age* for control (CON) in comparison with CAI and copers (COP) ($p<0.001$), and between CAI and COP ($p=0.018$). FADI[†] (Functional Ankle Disability Index) and FADI-S[‡] (Functional Ankle Disability Index-Sport subscale) score were significantly lower in the CAI group compared to both the control group and the copers group ($p<0.001$).

Experimental procedure

Baseline characteristics were registered for all subjects. The Foot and Ankle Disability Index (FADI) and its sport subscale (FADI-S) were completed by all participants to assess the disability of the ankle during daily living.¹⁴ Group characteristics are presented in table 1.

Subjects had to perform 2 landing tasks. First, subjects carried out a single leg vertical drop from a 40cm high box. They were instructed not to jump, but rather to step down, starting out on the opposite leg, from the box to control drop height and land onto the force plate. Balance had to be maintained for at least 3 seconds after landing. Hands had to be kept on the hips throughout the whole trial and subjects were asked to look straight forward. Trials were discarded if the subject jumped from the box, if the foot shifted after landing, if hands were used to restore balance, if there was contact between both legs in an attempt to keep balance, or if the contralateral foot touched the ground. Each subject performed 3 vertical drops. As second task, after 5min rest, subjects had to perform a maximal side jump. Subjects started in a unipodal position on their contralateral foot, were asked to push off and jump maximally sideways and land on their tested leg onto the force plate. The foot position upon landing had to be perpendicular to the line of movement to eliminate compensation by external rotation of the foot. A jump was discarded if the subject required any corrections following landing as described above. Each subject performed 3 side jumps.

All subjects were barefooted during testing and none complained of any discomfort during the functional tasks. In the CAI group, the most unstable ankle, based on the subject's medical history, was investigated. For the copers, the most recently sprained ankle within the last two years was selected. In the control group the tested foot was chosen at random. Subjects were permitted a period of practice in the jumping technique prior to testing.

Spherical reflective surface markers (7mm) were placed on anatomical landmarks according to the Ghent Foot Model. This six-segment model tracks the shank, rear foot, midfoot, medial and lateral forefoot, and the hallux as individual functional segments. The rigid foot was defined by markers on the calcaneus, the lateral malleolus, and the head of the first and fifth metatarsal head. A 6 camera opto-electronic system (500Hz, OQUS 3, Qualysis, Gothenburg, Sweden) was synchronized with a force plate (500Hz, AMTI, Watertown, Massachusetts) embedded underneath the landing zone to capture kinematic and kinetic data. A visual control record was captured by means of a normal video camera (Sony, 25Hz).

Data analysis

Visual 3D (C-motion, Germantown, MD) was used to process the kinematic and kinetic data (QTM, Qualysis). Marker data was filtered using a fourth order Butterworth low-pass filter at 15Hz, with 50 points reflected. Euler rotations (X-Y-Z, representing respectively dorsi-/plantar flexion, eversion/inversion, ab-/adduction) were used to calculate motion between the defined segments in the different planes.⁵ Joint kinematics were calculated for the impact phase which was defined from touch down (TD) until maximal dorsiflexion in the ankle joint (maxDF). The vertical component of the ground reaction force (threshold set at 15 N) was used for event detection. Additionally, range of motion (ROM) was determined for each joint during the impact phase. Furthermore, peak forces (normalized to body weight), time to peak forces and loading rate (normalized peak force/time to peak force) were calculated for the vertical component of the GRF. The raw force data were filtered by a critically damped low-pass filter at 15Hz.

A curve analysis of joint angles of the different segments of the GFM and the rigid foot was performed to compare between groups. The specific method used was one-dimensional statistical parametric mapping (SPM).^{12, 21} SPM allows the calculation of the traditional F and t statistics, subsequently referred to as $SPM\{F\}$ or $SPM\{t\}$, over the entire normalized time-series. For this analysis a SPM ANOVA followed by post-hoc SPM t-tests if appropriate, were used with alpha maintained at 0.05 throughout. Firstly, using SPM ANOVA a $SPM\{F\}$ was calculated. Secondly, the temporal smoothness of $SPM\{F\}$ based on the average temporal gradient was estimated. Subsequently, the threshold of $SPM\{F\}$ was computed above which only alpha=5% of the data would be expected to reach had the test statistic trajectory resulted from an equally smooth random process. Finally, Random Field Theory was used to handle the challenge of multiple comparisons and conducting inferential statistics. Individual probability values were calculated for each supra-threshold cluster based on the probability that a cluster of a given height and size could have resulted from an equivalently smooth random process. If

statistical significance was reached in the SPM{F} then the original data were further analysed with three pairwise post-hoc SPM t-tests, using the same processes as described above to establish the significance of the SPM{t} in paired groups.

Between group differences for ROMs, peak forces, time to peak force and loading rate were analyzed by means of a One Way ANOVA. Post hoc comparisons with a Bonferroni correction were performed to identify specific differences. Significance level was set at $p \leq 0.05$. Statistical analysis of these parameters was performed in SPSS 21 (SPSS Inc., Chicago, Illinois 60606, U.S.A.).

Results

Curve analysis

Vertical drop

The rigid foot (in relation to the shank) showed a less inverted position from approximately 10%-100% of the impact phase for both the CAI group ($p < 0.001$) and coper group ($p < 0.001$) compared to the control group (supplementary file 2, fig.3). During this period, the rigid foot is progressing towards a maximally inverted position. In addition, the CAI group (approx. 10-100%, $p < 0.001$) and coper group (approx. 15-20%, $p < 0.05$) displayed a more adducted position of the hallux (in relation to the medial forefoot) in comparison to the control group. In the CAI and coper group the hallux slightly adducts in the beginning of the impact phase before remaining in a stable position (supplementary file 2, fig.4). Adduction for the hallux signifies motion towards the subject's center sagittal plane.

Side jump

A less plantar flexed position was found for the rigid foot (supplementary file 2, fig. 5) and the rearfoot at touch down between both the CAI group (resp. approx. 0-10%, $p < 0.05$; approx. 0-10%, $p < 0.05$) and coper group (resp. approx. 0-10%, $p < 0.05$; approx. 0-15%, $p < 0.05$) compared to the control group. In addition, the coper group displayed a more dorsiflexed position of the rearfoot at the end of the impact phase from approximately 60-100% ($p < 0.05$) (fig 1). The rearfoot displayed also a significantly less inverted position from approximately 0-55% in the CAI group compared to the control group ($p < 0.05$) (supplementary file 2, fig.7). During this phase, the rearfoot first inverts followed by eversion which continues throughout the remainder of the impact phase. Furthermore, the CAI group had a more inverted position of the midfoot (in relation to the rearfoot) for approximately the whole impact phase compared

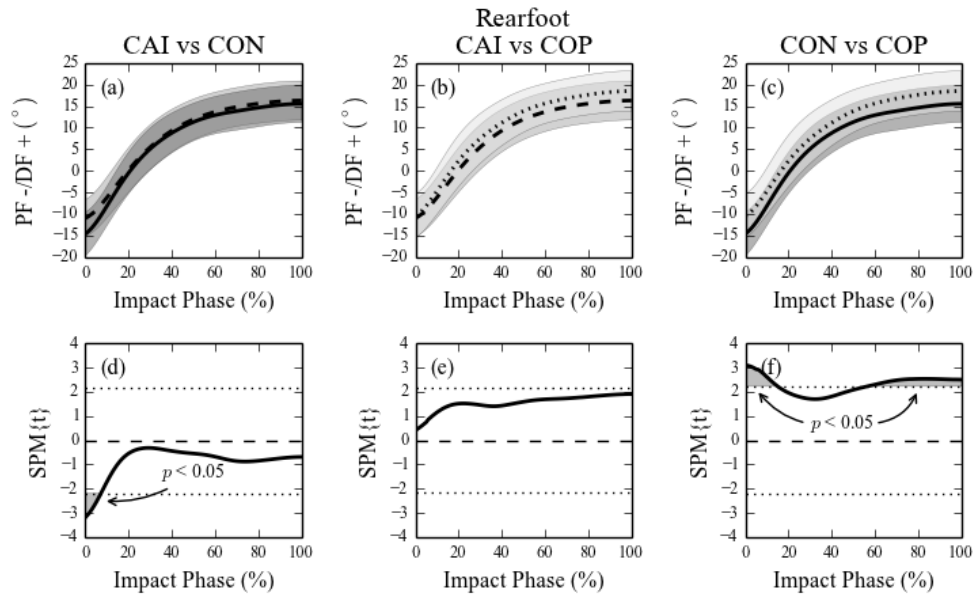


Figure 1. Kinematic between-group comparison of the rearfoot during a side jump landing task (CAI =dashed --; COP =dotted .; CON =solid _). (a,b,c) Mean ankle joint kinematic trajectories with standard deviation clouds. (d,e,f) Statistical Parametric Mapping results; "SPM{t}" is the trajectory Student's t statistic or, equivalently, the mean difference curve normalised by sample-size normalised variance. The dotted horizontal line indicates the random field theory threshold for significance, and p values indicate the likelihood that a random process of the same temporal smoothness would be expected to produce a supra-threshold cluster of the observed size.

to the control group (supplementary file 2, fig.8). After initially inverting, the midfoot describes an eversion motion until the end of the impact phase. Finally, the medial forefoot (in relation to the midfoot) in the copper group showed a more inverted position from approximately 55-100%, during which slight eversion takes place, in comparison to the control group ($p < 0.05$) (supplementary file 2, fig.9).

Range of Motion

Significant ANOVA results are presented in table 2. Post hoc analysis on the **vertical drop** data showed a significantly smaller ROM for rigid foot plantar-/ dorsiflexion in the CAI group compared to the control group ($p = 0.020$). Rigid foot abduction/adduction and rearfoot plantar-/dorsiflexion ROM did not reach significance level in post hoc analysis. Furthermore, the copper group displayed a smaller plantar-/dorsiflexion ROM in the lateral forefoot ($p = 0.030$), medial forefoot ($p = 0.017$) and hallux compared to the control group ($p = 0.028$). Finally, the midfoot showed less eversion/inversion ROM in the copper group compared to the CAI group ($p = 0.038$). For the **side jump**, the CAI group displayed less ROM in the rigid foot as well as the rearfoot for plantar-/dorsiflexion and ab-/adduction compared to the control group

(PF/DF: resp. $p=0.010$ and 0.045 ; ABD/ADD: resp. $p=0.003$ and 0.004). The copers group again displayed a smaller plantar-/dorsiflexion ROM in the lateral forefoot ($p=0.030$), and medial forefoot ($p=0.017$) compared to the control group. Finally, the hallux showed less eversion/inversion ROM in the copers group compared to the CAI group ($p=0.039$).

Table 2. Mean (SD) and significant ANOVA results for Range of Motion (ROM).

ROM	Vertical Drop (°)			
	CON	COP	CAI	P-value
Rigid Foot DF/PF	48.90 (5.51)*	47.48 (5.18)	45.09 (5.85)*	0.022*
Rigid Foot ABD/ADD	11.32 (3.15)	11.18 (3.19)	9.60 (2.89)	0.045
Rearfoot DF/PF	35.10 (4.71)	35.07 (4.07)	32.61 (4.99)	0.048
Midfoot EV/IN	2.01 (0.66)	1.85 (0.65) [†]	2.48 (1.36) [†]	0.030 [†]
Lateral forefoot DF/PF	28.90 (4.15) [‡]	25.78 (3.88) [‡]	27.33 (4.43)	0.021 [‡]
Medial forefoot DF/PF	26.32 (5.44) [‡]	22.23 (5.14) [‡]	23.73 (5.06)	0.019 [‡]
Hallux DF/PF	28.34 (5.32) [‡]	23.08 (4.29)	25.54 (7.43)	0.032 [‡]
ROM	Side Jump (°)			
	CON	COP	CAI	P-value
Rigid Foot DF/PF	43.05 (7.82)*	40.46 (6.16)	37.91 (6.59)*	0.013*
Rigid Foot ABD/ADD	13.60 (4.23)*	12.06 (4.11)	10.35 (3.40)*	0.005*
Rearfoot DF/PF	30.19 (5.54)*	28.93 (4.22)	27.28 (4.43)*	0.049*
Rearfoot ABD/ADD	8.35 (2.52)*	7.28 (2.27)	6.50 (2.00)*	0.006*
Lateral forefoot DF/PF	23.86 (5.69) [‡]	20.61 (4.68) [‡]	21.91 (5.13)	0.034 [‡]
Medial forefoot DF/PF	19.53 (6.47) [‡]	14.93 (5.68) [‡]	16.46 (5.32)	0.024 [‡]
Hallux EV/IN	23.16 (6.81)	28.44 (7.65) [†]	22.15 (8.65) [†]	0.035 [†]

CON=control group; COP=copers group; CAI=chronic ankle instability group; DF=dorsiflexion; PF=plantar flexion; EV=eversion; IN=inversion; ABD=abduction; ADD=adduction. Post hoc results ($p \leq 0.05$) are labeled with * for a significant difference between CAI and CON, with [‡] between COP and CON, and with [†] between COP and CAI.

Ground reaction force

The CAI group displayed a higher peak vertical GRF ($p=0.019$), reached this vertical peak faster ($p=0.021$), and had a higher loading rate ($p=0.008$) than the control group for the vertical drop. Means and ANOVA results are presented in table 3. For the side jump, no significant differences were found.

There was no significant difference between the control group, copers and CAI group regarding the time to reach the maxDF during the vertical drop (0.24s (SD 0.05), 0.23s (SD 0.07) and 0.22s (SD 0.05) respectively, $p=0.288$) and the side jump (0.24s (SD 0.05), 0.22s (SD 0.05) and 0.22s (SD 0.05) respectively, $p=0.342$). Significant post-hoc analysis results for curve analysis,

ROM, and GRF are presented below (supplementary file 1 presents all means, ANOVA results and post hoc results for ROM and GRF; supplementary file 2, which represents the kinematic curves for each segment in each plane and post hoc SPM comparisons).

Table 3. Mean (SD) and significant ANOVA results for vertical ground reaction force (GRF).

GRF	CON	COP	CAI	P-value
Time to peak vertical GRF (sec)	0.061 (0.015)*	0.055 (0.011)	0.052 (0.012)*	0.021*
Peak vertical GRF (/BW)	2.976 (0.401)*	3.197 (0.473)	3.273 (0.449)*	0.023*
Loading rate ((N/BW)/sec)	52.40 (16.46)*	61.63 (18.70)	66.85 (21.17)*	0.010*

CON=control group; COP=coper group; CAI=chronic ankle instability group; BW=body weight. Post hoc significant results between groups are labeled with * ($p \leq 0.05$).

Discussion

To our knowledge, this was the first study that described multi-segmented foot landing kinematics, with the main aim to explore whether any differences could be observed in subjects with CAI, copers and controls. Overall, we identified similar differences in the sagittal plane kinematics during the impact phase between groups for both the vertical drop and side jump. Differences were found between subjects with CAI, copers and controls at the rearfoot, midfoot, medial/lateral forefoot and hallux. Subjects with CAI and copers, seem to display a compensatory strategy by exhibiting less plantar flexion upon impact. This could protect them from a possible ankle sprain, as explained below. However, this strategy could be counterproductive, especially for those subjects who developed CAI. They demonstrated a stiffer landing pattern (smaller ROM) with higher loading rates, which may make them more susceptible for episodes of giving way and ankle sprains.

In the sagittal plane, subjects with CAI displayed a significantly less plantar flexed angle upon impact in both the rearfoot and rigid foot for the side jump compared to the control group. And although not significant, the kinematic data of the vertical drop suggest a similar pattern. These findings correspond with the results of Caulfield and Garrett⁴, who found a less plantar flexed ankle angle before, at, and post landing after a similar vertical drop. They argued that this less plantar flexion might be a protective mechanism to restrain the lateral ligament complex from harmful stretch. In addition, a model driven study suggested that increased plantar flexion at touch down might be the primary mechanism, more than the frontal plane subtalar joint angle, to have an increased susceptibility for ankle sprains.³⁰ Subjects with CAI might, therefore, try to limit plantar flexion at touch down as a protective strategy. However,

this protective strategy can at the same time be counterproductive. Their total ROM during the impact phase in the sagittal plane was reduced in the rigid foot for both the vertical drop and side jump, and in the rearfoot for the sidejump. In addition, ROM of transversal plane movements for the side jump was also limited in the rigid foot and the rearfoot in subjects with CAI. This more rigid strategy might suppress the capacity to react appropriately to external perturbations, and might have a negative influence on vertical impact forces as discussed further on.

In the frontal plane, a less inverted joint angle at the rearfoot was seen in the CAI group at touch down during the side jump, and at the rigid foot for most part towards the end of the impact phase for the vertical drop and the side jump. These findings are consistent with previous results using a multi-segmented foot model during gait, indicating a less inverted position of the rearfoot during midstance.⁶ Based on the pathomechanics of an ankle sprain, the less inverted position suggests again a compensation rather than causation. A prospective study by Willems et al.²⁸ using plantar pressure measurements during running found an increased medial loading of the foot and a trend of higher eversion excursion in subjects susceptible for an ankle sprain. They suggested that this more medial foot roll-off may be the result of a compensation mechanism for possible ankle sprains.²⁸ This compensation mechanism might also cause the lower inversion angles found in the current study. Our results, therefore, do not confirm previous findings in literature indicating a more inverted position of the ankle in the landing phase.^{9, 19}

Subjects with CAI displayed a more inverted position of the midfoot throughout the whole impact phase compared to controls during side jump and more midfoot in/eversion ROM compared to copers during vertical drop. The midfoot fulfills an important role in coupling rearfoot and forefoot motion.² Further research might elucidate the impact of midfoot kinematics observed in the current study by investigating the forefoot and rearfoot coupling in CAI. Furthermore, differences in hallux kinematics have been observed, namely for the vertical drop a more adducted hallux position for subjects with CAI (10%-100% of impact phase) and copers (15%-20% of impact phase) compared to controls and less plantar-/dorsiflexion ROM in the coper group compared to controls, and for the side jump a smaller eversion/inversion ROM in the coper group compared to the subjects with CAI. These varying results between conditions and groups hamper a clear interpretation on the possible underlying mechanisms. Future research is necessary to confirm the above mechanisms and to study their consistency during other functional movements. Monitoring muscle activity combined with the foot kinematics might provide deeper insight in the described mechanisms.

The CAI group exhibited both an earlier, as well as a higher peak vertical GRF, during the vertical drop which has been pointed out previously in other studies.^{3, 8} This suggested that the CAI group is exposed to higher loading rates²⁹, as supported by our results, which would match our earlier notion of a stiffer landing pattern in the smaller ROM. We checked this by calculating Pearson correlation coefficients and a significant correlation was found between the plantar-/dorsiflexion ROM of the rigid foot, and the load rate, defined as the normalized peak vertical GRF divided by the time to peak vertical GRF ($p < 0.001$, $r = -0.689$) (fig 2).²⁹ Increased loading rates may very well put a subject at risk for sustaining an injury because of possible limited capacity to absorb this higher loading. Several studies have indicated neuromuscular insufficiencies in the preparatory and response phase in subjects with CAI which might prevent them from adequately controlling the foot complex to accommodate for these forces.^{7, 16, 25} Figure 2 also shows that within the CAI group, there is substantial variation in stiffness of the landing, which may help focus treatment for those individuals with CAI who show increased landing stiffness. For the side jump, no significant differences were found in force dissipation between the study groups. A possible explanation for this dissimilarity in results between conditions could be attributed to movement direction. Logically, a vertical drop will have greater impact on the vertical GRF than will a side jump movement, and could therefore be more sensitive to group differences.

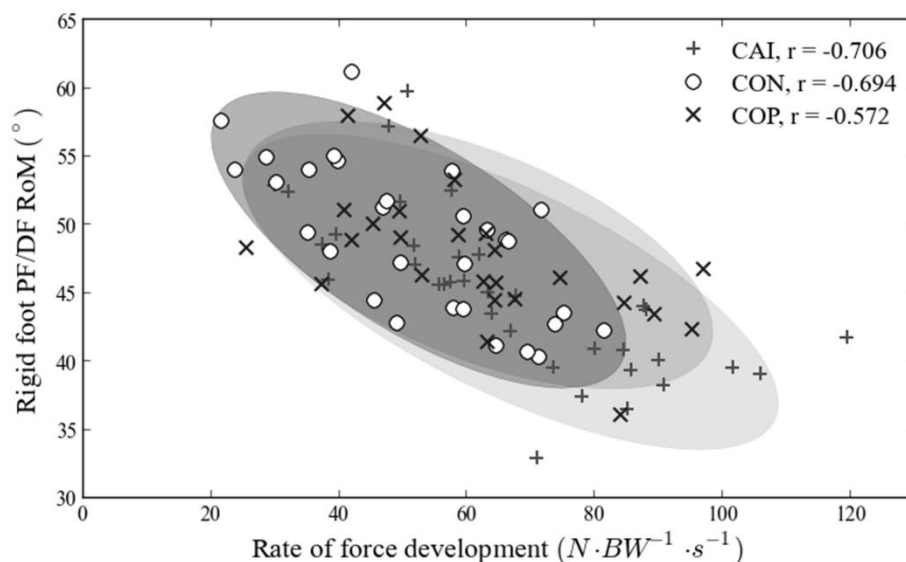


Figure 2. Scatterplot visualizing correlation between the dorsiflexion/plantar flexion range of motion (DF/PF ROM) and the rate of force development with co-variance cloud (2 SD) for each group (dark=CON, mediate=COP, light=CAI).

When observing the copers group, interesting differences are reported compared to the control group. For the side jump, a similar lower plantar flexion angle as in the CAI group was registered for the rearfoot and the rigid foot. Unlike the CAI group, however, the copers had no significantly decreased ROM in the rigid foot and rearfoot during the impact phase. On the contrary, the copers group had a more dorsiflexed joint angle at the end of the impact phase for the side jump compared to the controls, indicating a more closed packed position, which is considered a locked and therefore stable position of the joint.¹⁷ This could protect them from possible episodes of giving way and ankle sprain events. Furthermore, the copers group had significantly less ROM in the medial and lateral forefoot for both vertical drop and side jump compared to the control group. The underlying mechanism responsible for this consistent giving, is unclear to the authors, but might be part of some sort of coping strategy.

Some methodological limitations related to this study have to be borne in mind. Both jumping conditions occurred barefooted. A recent study by Shultz et al.²⁴ concluded that shod versus barefoot landings may alter impact forces that modulate stiffness strategies. This should be taken into account when comparing and extrapolating study results. For the side jump protocol, a maximal effort/distance jump was chosen to provoke subjects' landing control capabilities. The jump distance was not taken into account in the study results and may have differed between groups. Similar foot landing kinematics were found in the vertical drop and maximal side jump conditions, indicating that both tasks offer a means to recognize group effects. Whether a maximal side jump is necessary, or a submaximal distance jump could suffice, is uncertain. Fleischmann et al.¹⁰ found no differences in angular displacement at the ankle joint during landing jumps at different distances, so for now we could consider that submaximal jumps may well have revealed the same group effects, yet this still needs to be seen. Furthermore, analysis of the data has been performed within the exploratory nature of the current study. Significance level of the SPM analyses was not corrected for the dependent planes of joint motion, as in a previous paper.⁶ This liberal approach was chosen as it prevents that potentially weak phenomena would immediately be dismissed at this early stage of multi-segmented foot model explorations. For data collection, due to technical limitations of the capturing volume, centre of mass determination and pre-impact kinematics were not registered. This means that joint moments and center of mass position could not be calculated and important pre-impact kinematic landing differences could have been missed. Future research should therefore also include e.g. pre-landing observations if possible, particularly if that were to involve the study of muscle (pre-)activations.

Conclusions

The use of a multi-segmented foot model shows promising results for identifying possible influencing factors related to chronic ankle instability. Subjects with CAI displayed an altered, stiffer foot landing kinematic strategy and adapted kinetic landing characteristics compared to a control group, which might predispose them for episodes of giving way and actual ankle sprain events. However, further research is warranted to increase the insight in foot and ankle kinematics during functional tasks, and gain a better understanding of underlying mechanisms of CAI.

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References

- (1) Anandacoomarasamy A, Barnsley L. Long term outcomes of inversion ankle injuries. *Br J Sports Med* 2005;39(3):e14.
- (2) Blackwood CB, Yuen TJ, Sangeorzan BJ, Ledoux WR. The midtarsal joint locking mechanism. *Foot Ankle Int* 2005;26(12):1074-1080.
- (3) Caulfield B, Garrett M. Changes in ground reaction force during jump landing in subjects with functional instability of the ankle joint. *Clin Biomech (Bristol , Avon)* 2004;19(6):617-621.
- (4) Caulfield BM, Garrett M. Functional instability of the ankle: differences in patterns of ankle and knee movement prior to and post landing in a single leg jump. *Int J Sports Med* 2002;23(1):64-68.
- (5) De Mits S, Segers V, Woodburn J, Elewaut D, De Clercq D, Roosen P. A clinically applicable six-segmented foot model. *J Orthop Res* 2011.
- (6) De Ridder R, Willems T, Vanrenterghem J, Robinson M, Pataky T, Roosen P. Gait Kinematics of Subjects with Ankle Instability Using a Multisegmented Foot Model. *Med Sci Sports Exerc* 2013.
- (7) Delahunt E, Monaghan K, Caulfield B. Altered neuromuscular control and ankle joint kinematics during walking in subjects with functional instability of the ankle joint. *Am J Sports Med* 2006;34(12):1970-1976.
- (8) Delahunt E, Monaghan K, Caulfield B. Changes in lower limb kinematics, kinetics, and muscle activity in subjects with functional instability of the ankle joint during a single leg drop jump. *J Orthop Res* 2006;24(10):1991-2000.
- (9) Delahunt E, Monaghan K, Caulfield B. Ankle function during hopping in subjects with functional instability of the ankle joint. *Scand J Med Sci Sports* 2007;17(6):641-648.
- (10) Fleischmann J, Gehring D, Mornieux G, Gollhofer A. Load-dependent movement regulation of lateral stretch shortening cycle jumps. *Eur J Appl Physiol* 2010;110(1):177-187.
- (11) Fong DT, Hong Y, Chan LK, Yung PS, Chan KM. A systematic review on ankle injury and ankle sprain in sports. *Sports Med* 2007;37(1):73-94.
- (12) Friston K, Ashburner J, Kiebel S, et al., Eds. *Statistical Parametric Mapping: The Analysis of Functional Brain Images*. London, United Kingdom: Elsevier; 2011, 656 pp.
- (13) Gribble P, Robinson R. Differences in spatiotemporal landing variables during a dynamic stability task in subjects with CAI. *Scand J Med Sci Sports* 2010;20(1):e63-e71.
- (14) Hale SA, Hertel J. Reliability and Sensitivity of the Foot and Ankle Disability Index in Subjects With Chronic Ankle Instability. *J Athl Train* 2005;40(1):35-40.
- (15) Hertel J. Functional Anatomy, Pathomechanics, and Pathophysiology of Lateral Ankle Instability. *J Athl Train* 2002;37(4):364-375.
- (16) Hopkins JT, Brown TN, Christensen L, Palmieri-Smith RM. Deficits in peroneal latency and electromechanical delay in patients with functional ankle instability. *J Orthop Res* 2009;27(12):1541-1546.
- (17) Kaltzenborn F. *Mobilization of the extremity joints*. 3rd ed. Olaf Norlis Bokhandel; 1980.
- (18) Konradsen L, Bech L, Ehrenbjerg M, Nickelsen T. Seven years follow-up after ankle inversion trauma. *Scand J Med Sci Sports* 2002;12(3):129-135.
- (19) Lin CF, Chen CY, Lin CW. Dynamic ankle control in athletes with ankle instability during sports maneuvers. *Am J Sports Med* 2011;39(9):2007-2015.
- (20) Morrison KE, Kaminski TW. Foot characteristics in association with inversion ankle injury. *J Athl Train* 2007;42(1):135-142.
- (21) Pataky TC. Generalized n-dimensional biomechanical field analysis using statistical parametric mapping. *J Biomech* 2010;43(10):1976-1982.

- (22) Rankine L, Long J, Canseco K, Harris GF. Multisegmental foot modeling: a review. *Crit Rev Biomed Eng* 2008;36(2-3):127-181.
- (23) Renstrom PA, Konradsen L. Ankle ligament injuries. *Br J Sports Med* 1997;31(1):11-20.
- (24) Shultz SJ, Schmitz RJ, Tritsch AJ, Montgomery MM. Methodological considerations of task and shoe wear on joint energetics during landing. *J Electromyogr Kinesiol* 2012;22(1):124-130.
- (25) Suda EY, Amorim CF, Sacco IC. Influence of ankle functional instability on the ankle electromyography during landing after volleyball blocking. *J Electromyogr Kinesiol* 2009;19(2):e84-e93.
- (26) Valderrabano V, Hintermann B, Horisberger M, Fung TS. Ligamentous posttraumatic ankle osteoarthritis. *Am J Sports Med* 2006;34(4):612-620.
- (27) van Rijn RM, van Os AG, Bernsen RM, Luijsterburg PA, Koes BW, Bierma-Zeinstra SM. What is the clinical course of acute ankle sprains? A systematic literature review. *Am J Med* 2008;121(4):324-331.
- (28) Willems T, Witvrouw E, Delbaere K, De Cock A, De Clercq D. Relationship between gait biomechanics and inversion sprains: a prospective study of risk factors. *Gait Posture* 2005;21(4):379-387.
- (29) Williams DS, III, Davis IM, Scholz JP, Hamill J, Buchanan TS. High-arched runners exhibit increased leg stiffness compared to low-arched runners. *Gait Posture* 2004;19(3):263-269.
- (30) Wright IC, Neptune RR, van den Bogert AJ, Nigg BM. The influence of foot positioning on ankle sprains. *J Biomech* 2000;33(5):513-519.
- (31) Yeung MS, Chan KM, So CH, Yuan WY. An epidemiological survey on ankle sprain. *Br J Sports Med* 1994;28(2):112-116.
- (32) Zhang SN, Bates BT, Dufek JS. Contributions of lower extremity joints to energy dissipation during landings. *Med Sci Sports Exerc* 2000;32(4):812-819.

Supplemental file 1: Mean, standard deviation and ANOVA results (table 1), and post hoc results (table 2) for rigid and multi-segmented kinematic group comparison for range of motion (ROM), and ANOVA results (table 3) and post hoc results (table 4) for vertical ground reaction force (GRF) for both vertical drop and side jump.

Range of motion Joint angle	Vertical Drop (°)				Side Jump (°)			
	CON (n=30)	COP (n=28)	CAI (n=38)	P-value	CON (n=30)	COP (n=28)	CAI (n=38)	P-value
Rigid Foot DF/PF	48.90 (5.51)	47.48 (5.18)	45.09 (5.85)	0.022*	43.05 (7.82)	40.46 (6.16)	37.91 (6.59)	0.013*
Rigid Foot EV/INV	11.03 (3.33)	9.45 (3.67)	9.90 (4.25)	0.265	13.39 (3.88)	13.01 (3.89)	13.36 (4.22)	0.921
Rigid Foot ABD/ADD	11.32 (3.15)	11.18 (3.19)	9.60 (2.89)	0.045*	13.60 (4.23)	12.06 (4.11)	10.35 (3.40)	0.005*
Rearfoot DF/PF	35.10 (4.71)	35.07 (4.07)	32.61 (4.99)	0.049*	30.19 (5.54)	28.93 (4.22)	27.28 (4.43)	0.048*
Rearfoot EV/INV	5.28 (2.14)	5.69 (1.94)	5.35 (1.77)	0.693	6.83 (2.53)	6.99 (2.00)	6.26 (2.28)	0.405
Rearfoot ABD/ADD	9.16 (2.61)	8.89 (2.80)	7.83 (2.06)	0.073	8.35 (2.52)	7.28 (2.27)	6.50 (2.00)	0.006*
Midfoot DF/PF	5.95 (1.84)	5.88 (1.87)	6.47 (2.99)	0.534	6.04 (2.53)	5.93 (2.04)	5.69 (2.31)	0.818
Midfoot EV/INV	2.01 (0.66)	1.85 (0.65)	2.48 (1.36)	0.030*	2.60 (1.07)	3.09 (1.62)	2.74 (1.20)	0.336
Midfoot ABD/ADD	4.63 (1.20)	4.36 (1.18)	4.36 (1.28)	0.615	3.21 (1.39)	3.14 (1.42)	2.99 (1.18)	0.790
Lateral Forefoot DF/PF	28.90 (4.15)	25.78 (3.88)	27.33 (4.43)	0.021*	23.86 (5.69)	20.61 (4.68)	21.91 (5.13)	0.034*
Lateral Forefoot EV/IN	5.18 (1.69)	5.43 (2.34)	4.64 (2.16)	0.297	7.81 (3.11)	7.78 (2.95)	8.01 (3.16)	0.948
Lateral Forefoot ABD/ADD	5.52 (1.71)	5.96 (1.89)	6.04 (1.75)	0.470	4.95 (2.06)	4.78 (1.46)	4.53 (1.73)	0.639
Medial Forefoot DF/PF	26.32 (5.44)	22.23 (5.14)	23.73 (5.06)	0.030*	19.53 (6.47)	14.93 (5.68)	16.46 (5.32)	0.024*
Medial Forefoot EV/INV	22.56 (10.84)	25.41 (8.41)	22.27 (9.87)	0.491	23.78 (9.04)	29.10 (8.01)	23.81 (10.57)	0.089
Medial Forefoot ABD/ADD	6.10 (2.36)	6.10 (2.27)	6.62 (2.87)	0.677	5.83 (2.67)	7.91 (3.72)	7.39 (3.93)	0.098
Hallux DF/PF	28.34 (5.32)	23.08 (4.29)	25.54 (7.43)	0.032*	25.58 (6.52)	23.36 (5.71)	25.68 (8.87)	0.556
Hallux EV/INV	20.69 (7.01)	18.00 (7.00)	24.05 (10.26)	0.071	23.16 (6.81)	28.44 (7.65)	22.15 (8.65)	0.035*
Hallux ABD/ADD	9.06 (5.38)	8.47 (4.39)	11.01 (6.28)	0.274	9.51 (4.22)	9.83 (5.54)	10.33 (7.87)	0.274

Table 1. Mean, standard deviation () and ANOVA results for range of motion during impact phase (* $p \leq 0.05$). CON=control group; COP=coper group; CAI=chronic ankle instability group; DF=dorsiflexion; PF=plantar flexion; EV=eversion; INV=inversion; ABD=abduction; ADD=adduction.

Vertical Drop							Side Jump						
Joint plane	group comparison	Mean Diff	Std. Error	Sig.	95% Confidence Interval		Joint plane	Group comparison	Mean Diff	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound						Lower Bound	Upper Bound
Rigid foot DF/PF	CON vs COP	1.42	1.46	0.999	-2.14	4.97	Rigid foot DF/PF	CON vs COP	2.59	1.81	0.47	-1.83	7.00
	CON vs CAI	3.81	1.37	0.02*	0.46	7.15		CON vs CAI	5.14	1.70	0.01*	0.99	9.29
	COP vs CAI	2.39	1.40	0.273	-1.02	5.80		COP vs CAI	2.55	1.74	0.435	-1.68	6.79
Rigid foot ABD/ADD	CON vs COP	0.14	0.81	1	-1.82	2.11	Rigid foot ABD/ADD	CON vs COP	1.53	1.02	0.412	-0.96	4.03
	CON vs CAI	1.71	0.76	0.078	-0.13	3.56		CON vs CAI	3.24	0.96	0.003*	0.90	5.59
	COP vs CAI	1.57	0.77	0.134	-0.31	3.46		COP vs CAI	1.71	0.98	0.254	-0.68	4.10
Rearfoot DF/PF	CON vs COP	0.02	1.22	1	-2.96	3.00	Rearfoot DF/PF	CON vs COP	1.26	1.25	0.951	-1.79	4.31
	CON vs CAI	2.48	1.15	0.099	-0.32	5.28		CON vs CAI	2.91	1.18	0.045*	0.04	5.78
	COP vs CAI	2.46	1.17	0.114	-0.39	5.32		COP vs CAI	1.66	1.20	0.512	-1.27	4.58
Midfoot EV/IN	CON vs COP	0.16	0.26	1	-0.47	0.79	Rearfoot ABD/ADD	CON vs COP	1.07	0.59	0.223	-0.38	2.52
	CON vs CAI	-0.48	0.24	0.166	-1.07	0.12		CON vs CAI	1.85	0.56	0.004*	0.49	3.21
	COP vs CAI	-0.64	0.25	0.038*	-1.24	-0.03		COP vs CAI	0.78	0.57	0.528	-0.61	2.16
Lateral forefoot DF/PF	CON vs COP	3.12	1.10	0.017*	0.44	5.80	Lateral forefoot DF/PF	CON vs COP	3.25	1.31	0.046*	0.05	6.45
	CON vs CAI	1.58	1.03	0.392	-0.95	4.10		CON vs CAI	2.56	1.24	0.123	-0.45	5.58
	COP vs CAI	-1.55	1.05	0.438	-4.12	1.03		COP vs CAI	-0.69	1.26	1	-3.76	2.38
Medial forefoot DF/PF	CON vs COP	4.09	1.55	0.03*	0.29	7.89	Medial forefoot DF/PF	CON vs COP	4.60	1.70	0.025*	0.44	8.76
	CON vs CAI	2.60	1.41	0.205	-0.84	6.04		CON vs CAI	3.07	1.56	0.159	-0.76	6.89
	COP vs CAI	-1.49	1.49	0.964	-5.15	2.17		COP vs CAI	-1.53	1.62	1	-5.50	2.43
Hallux DF/PF	CON vs COP	5.25	1.96	0.028*	0.43	10.08	Hallux EV/IN	CON vs COP	-5.28	2.55	0.128	-11.56	1.00
	CON vs CAI	2.80	1.74	0.34	-1.49	7.09		CON vs CAI	1.01	2.31	1	-4.69	6.70
	COP vs CAI	-2.45	1.88	0.591	-7.08	2.17		COP vs CAI	6.29	2.46	0.039*	0.24	12.34

Table 2. Post hoc analysis for significant ANOVA results for range of motion (* $p \leq 0.05$) CON=control group; COP=coper group; CAI=chronic ankle instability group; DF=dorsiflexion; PF=plantar flexion; EV=eversion; IN=inversion; ABD=abduction; ADD=adduction.

Vertical GRF	Vertical Drop				Side Jump			
	CON (n=30)	COP (n=28)	CAI (n=38)	P-value	CON (n=30)	COP (n=28)	CAI (n=38)	P-value
Time to peak vertical GRF (sec)	0.061 (0.015)*	0.055 (0.011)	0.052 (0.012)*	0.021*	0.082 (0.018)	0.080 (0.019)	0.084 (0.025)	0.641
Peak vertical GRF (/BW)	2.976 (0.401)*	3.197 (0.473)	3.273 (0.449)*	0.023*	2.043 (0.272)	2.127 (0.334)	2.173 (0.365)	0.276
Loading rate ((N/BW)/sec)	52.40 (16.46)*	61.63 (18.70)	66.85 (21.17)*	0.010*	26.53 (8.76)	28.49 (9.27)	29.36 (14.13)	0.598

Table 3. Mean, standard deviation () and ANOVA results for time to peak, maximal peak (normalized to body weight (BW)) and loading rate of the vertical ground reaction force (GRF) normalized to body weight (BW). * indicates between group post hoc significant results.

Vertical GRF	group comparison	Vertical Drop				
		Mean Diff	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Time to peak GRF	CON vs COP	0.006	0.003	0.214	-0.001	0.016
	CON vs CAI	0.009	0.003	0.019*	0.001	0.017
	COP vs CAI	0.003	0.003	1	-0.007	0.010
Peak vertical GRF(/BW)	CON vs COP	-0.22	0.12	0.185	-0.52	0.05
	CON vs CAI	-0.30	0.11	0.021*	-0.56	-0.03
	COP vs CAI	-0.08	0.11	1	-0.33	0.20
Loading rate ((N/BW)/sec)	CON vs COP	-9.23	5.06	0.214	-25.66	1.11
	CON vs CAI	-14.46	4.66	0.008*	-26.94	-1.76
	COP vs CAI	-5.22	4.81	0.840	-14.91	10.76

Table 4. Post hoc analysis for significant ANOVA results for vertical ground reaction force (GRF)(* $p \leq 0.05$) CON=control group; COP=coper group; CAI=chronic ankle instability group.

Supplemental file 2: Impact phase kinematic graphs for vertical drop (fig 1) and side jump (fig 2); post hoc SPM results (fig 3-9).

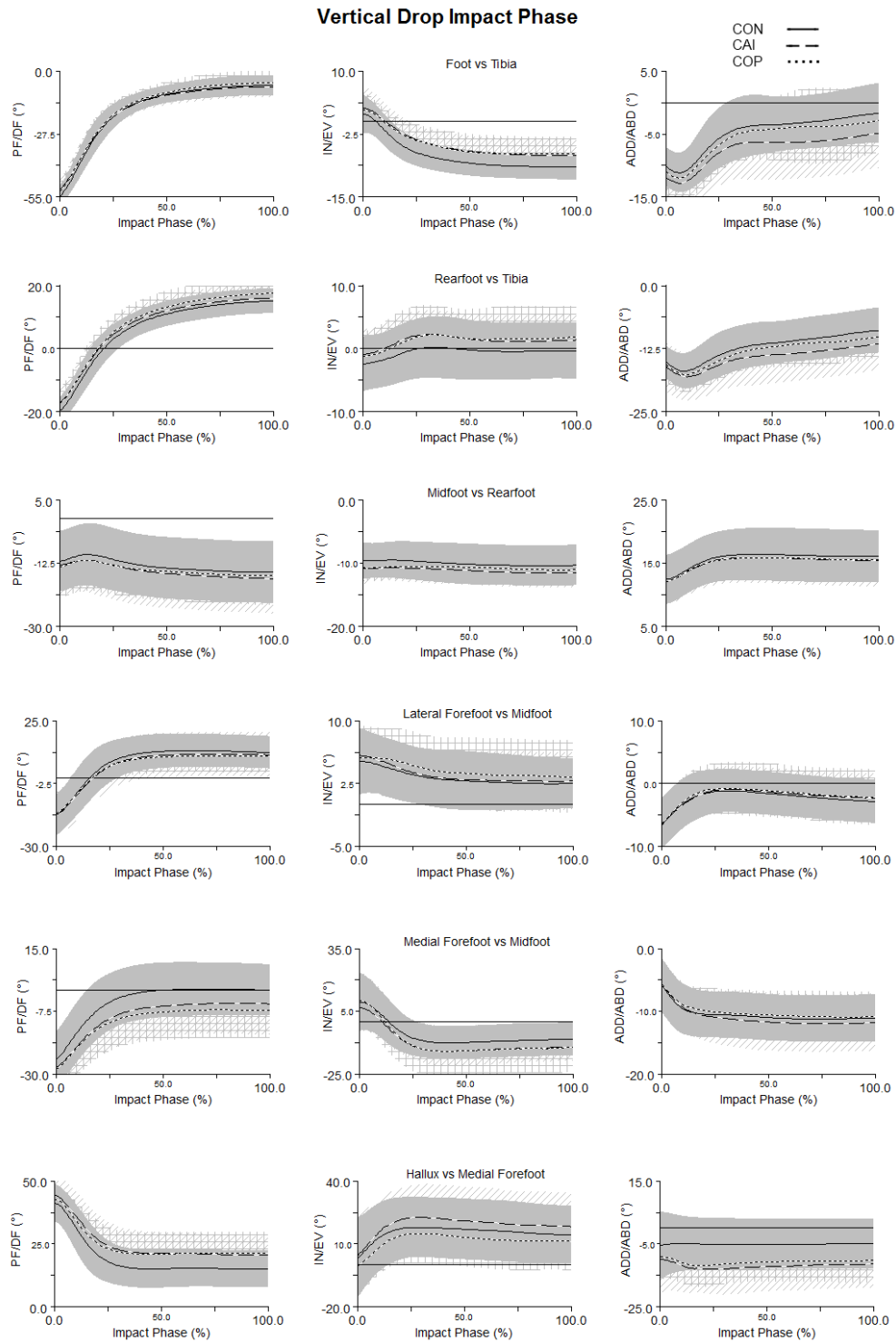


Figure 1. Rigid and multi-segmented foot kinematics during vertical drop impact phase: CON=control group (SD=grey); COP=coper group (SD=vertical raster); CAI=chronic ankle instability group (SD=diagonally up); DF=dorsiflexion(+); PF=plantar flexion(-); EV=eversion(+); IN=inversion(-); ABD=abduction(+); ADD=adduction(-)

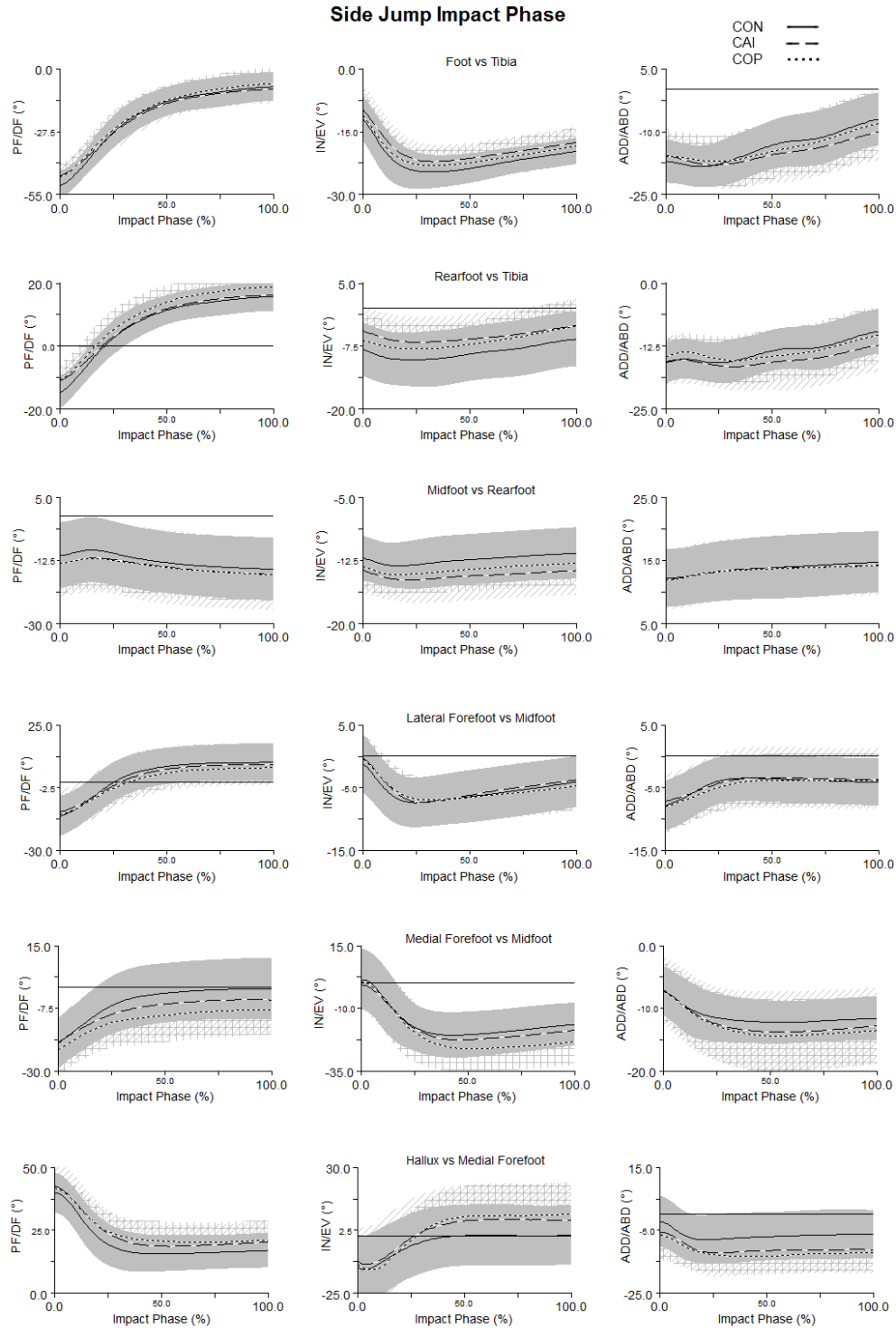


Figure 2. Rigid and multi-segmented foot kinematics during side jump impact phase: CON=control group (SD=grey); COP=coper group (SD=vertical raster); CAI=chronic ankle instability group (SD=diagonally up); DF=dorsiflexion(+); PF=plantar flexion(-); EV=eversion(+); IN=inversion(-); ABD=abduction(+); ADD=adduction(-)

Vertical Drop

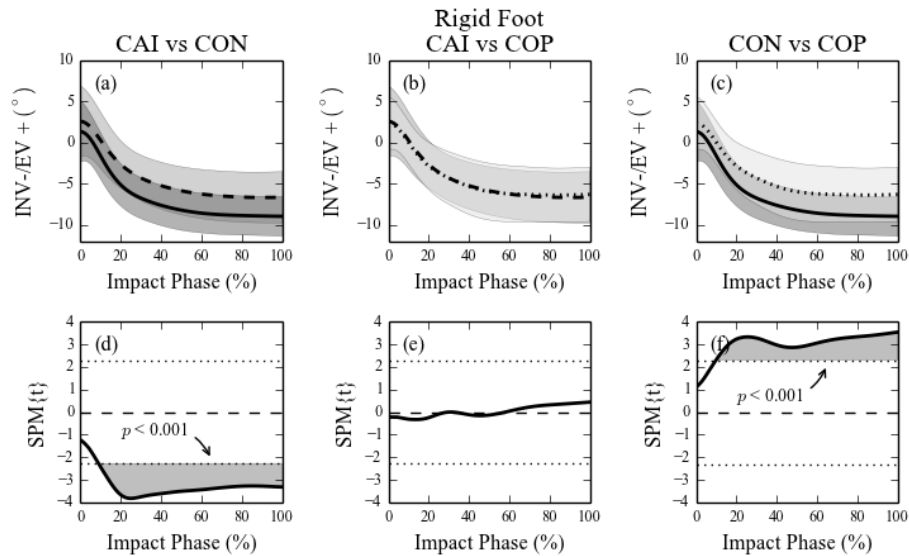


Figure 3. Kinematic between-group comparison of inversion/eversion joint angle of the rigid foot during a vertical drop landing task (CAI =dashed --; COP =dotted .; CON=solid __). (a,b,c) Mean ankle joint kinematic trajectories with standard deviation clouds. (d,e,f) Statistical Parametric Mapping results; "SPM{t}" is the trajectory Student's t statistic or, equivalently, the mean difference curve normalised by sample-size normalised variance. The dotted horizontal line indicates the random field theory threshold for significance, and p values indicate the likelihood that a random process of the same temporal smoothness would be expected to produce a supra-threshold cluster of the observed size.

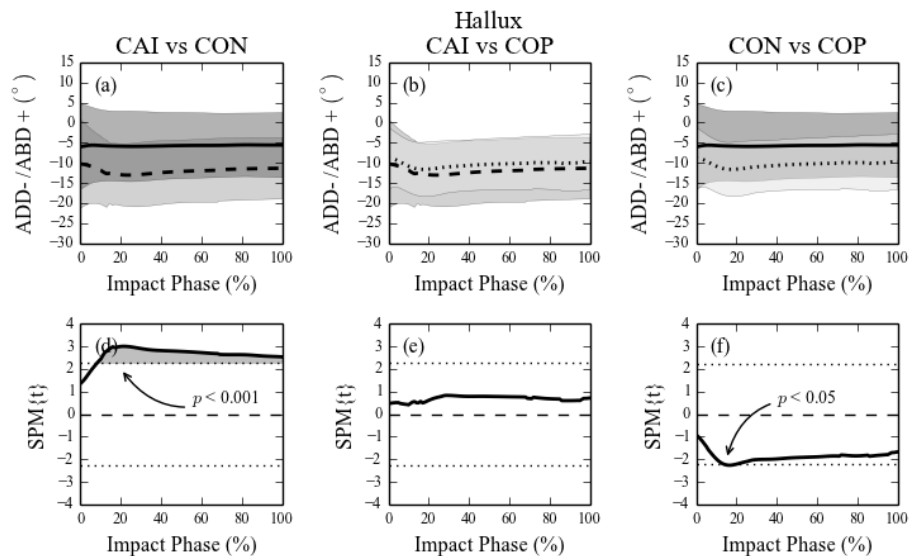


Figure 4. Kinematic between-group comparison of adduction/abduction joint angle of the hallux during a vertical drop landing task (CAI =dashed --; COP =dotted .; CON=solid __). (a,b,c) Mean ankle joint kinematic trajectories with standard deviation clouds. (d,e,f) Statistical Parametric Mapping results; "SPM{t}" is the trajectory Student's t statistic or, equivalently, the mean difference curve normalised by sample-size normalised variance. The dotted horizontal line indicates the random field theory threshold for significance, and p values indicate the likelihood that a random process of the same temporal smoothness would be expected to produce a supra-threshold cluster of the observed size.

Side Jump

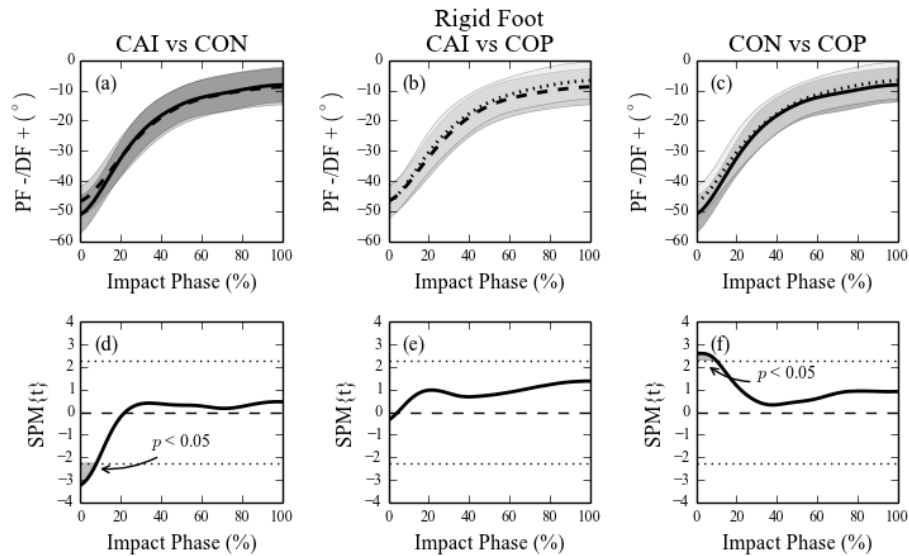


Figure 5. Kinematic between-group comparison of plantar-/dorsiflexion joint angle of the rigid foot during a side jump landing task (CAI =dashed --; COP =dotted .; CON =solid _). (a,b,c) Mean ankle joint kinematic trajectories with standard deviation clouds. (d,e,f) Statistical Parametric Mapping results; "SPM{t}" is the trajectory Student's t statistic or, equivalently, the mean difference curve normalised by sample-size normalised variance. The dotted horizontal line indicates the random field theory threshold for significance, and p values indicate the likelihood that a random process of the same temporal smoothness would be expected to produce a supra-threshold cluster of the observed size.

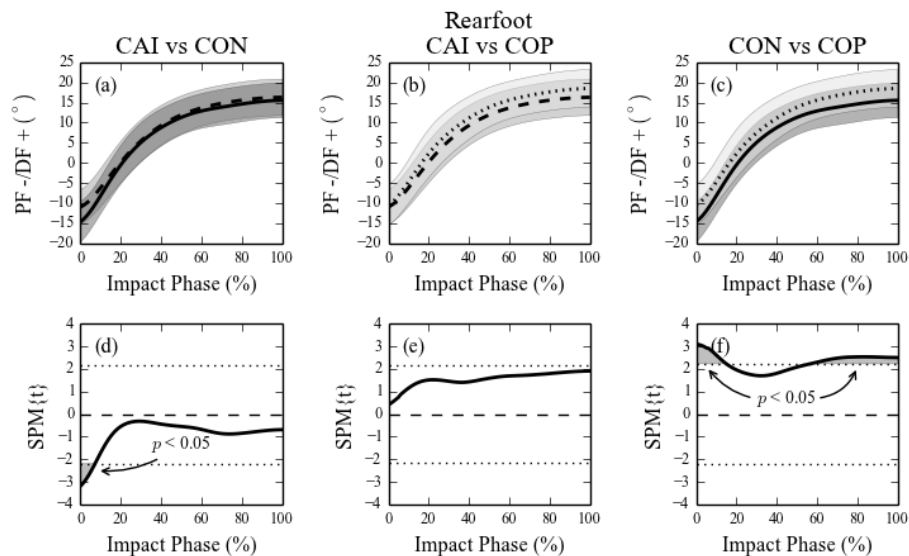


Figure 6. Kinematic between-group comparison of plantar-/dorsiflexion joint angle of the rearfoot during a side jump landing task (CAI =dashed --; COP =dotted .; CON =solid _). (a,b,c) Mean ankle joint kinematic trajectories with standard deviation clouds. (d,e,f) Statistical Parametric Mapping results; "SPM{t}" is the trajectory Student's t statistic or, equivalently, the mean difference curve normalised by sample-size normalised variance. The dotted horizontal line indicates the random field theory threshold for significance, and p values indicate the likelihood that a random process of the same temporal smoothness would be expected to produce a supra-threshold cluster of the observed size.

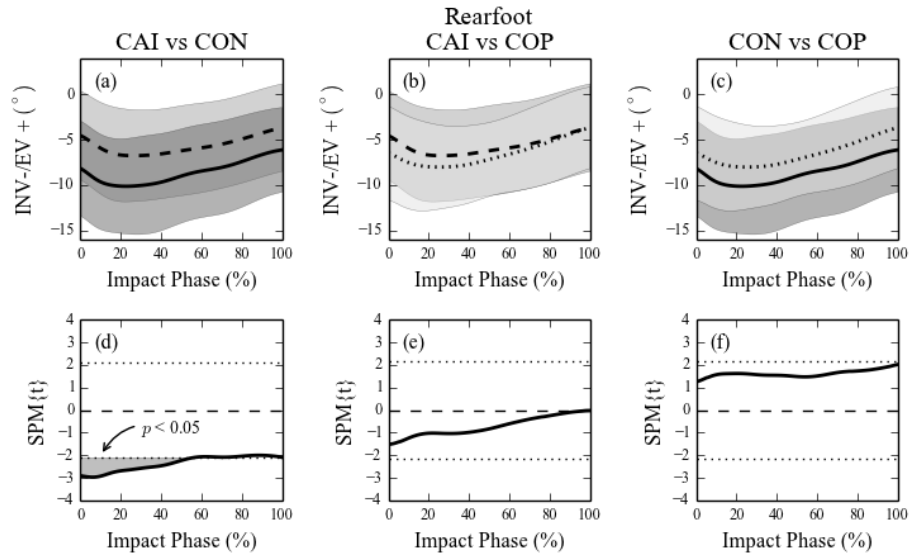


Figure 7. Kinematic between-group comparison of inversion/eversion joint angle of the rearfoot during a side jump landing task (CAI =dashed --; COP =dotted .; CON =solid _). (a,b,c) Mean ankle joint kinematic trajectories with standard deviation clouds. (d,e,f) Statistical Parametric Mapping results; "SPM{t}" is the trajectory Student's t statistic or, equivalently, the mean difference curve normalised by sample-size normalised variance. The dotted horizontal line indicates the random field theory threshold for significance, and p values indicate the likelihood that a random process of the same temporal smoothness would be expected to produce a supra-threshold cluster of the observed size.

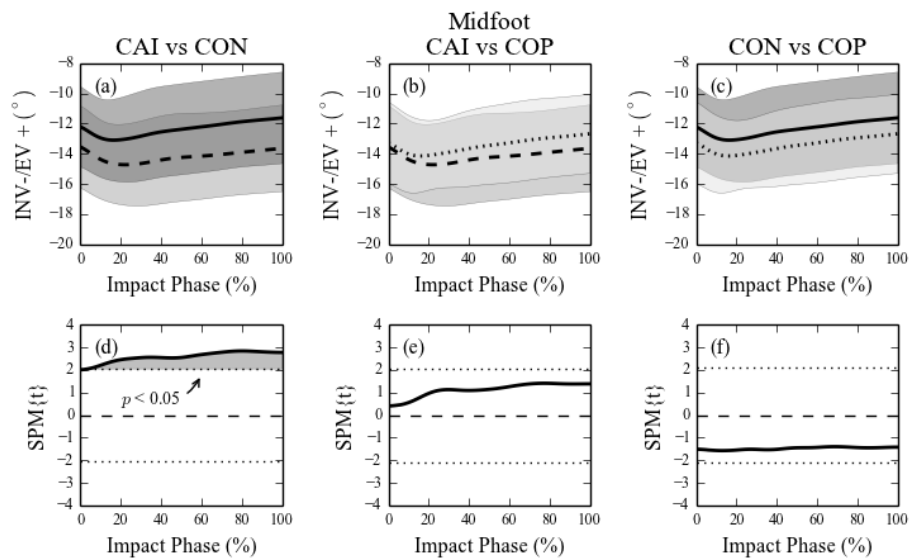


Figure 8. Kinematic between-group comparison of inversion/eversion joint angle of the midfoot during a side jump landing task (CAI =dashed --; COP =dotted .; CON =solid _). (a,b,c) Mean ankle joint kinematic trajectories with standard deviation clouds. (d,e,f) Statistical Parametric Mapping results; "SPM{t}" is the trajectory Student's t statistic or, equivalently, the mean difference curve normalised by sample-size normalised variance. The dotted horizontal line indicates the random field theory threshold for significance, and p values indicate the likelihood that a random process of the same temporal smoothness would be expected to produce a supra-threshold cluster of the observed size.

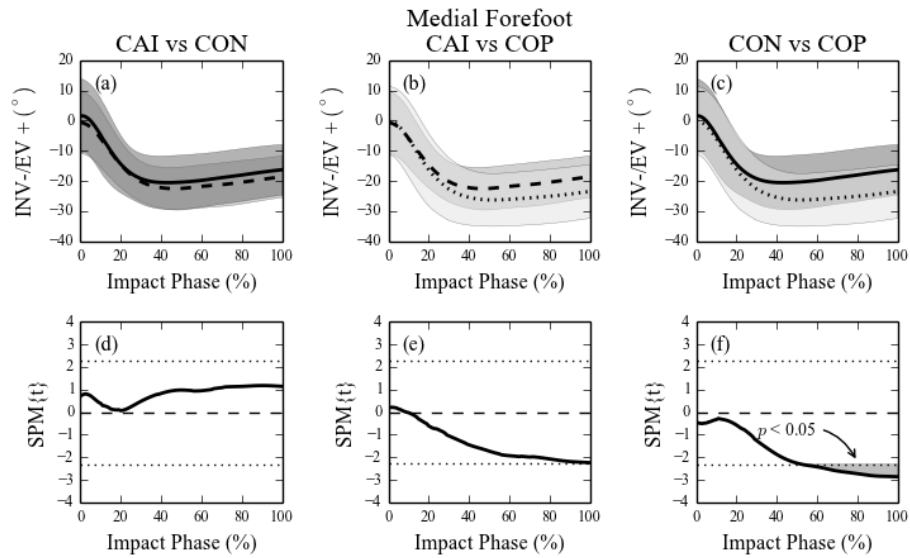


Figure 9. Kinematic between-group comparison of inversion/eversion joint angle of the medial forefoot during a side jump landing task (CAI =dashed --; COP =dotted .; CON =solid _). (a,b,c) Mean ankle joint kinematic trajectories with standard deviation clouds. (d,e,f) Statistical Parametric Mapping results; "SPM{t}" is the trajectory Student's t statistic or, equivalently, the mean difference curve normalised by sample-size normalised variance. The dotted horizontal line indicates the random field theory threshold for significance, and p values indicate the likelihood that a random process of the same temporal smoothness would be expected to produce a supra-threshold cluster of the observed size.

**Effect of balance training on dynamic postural control in
subjects with ankle instability**

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Abstract

Objective: The aim of this study was to establish the presence of postural deficits in subjects with chronic ankle instability (CAI) and to assess the effect of an 8-week balance training program on dynamic postural control.

Methods: A total of 43 subjects with CAI and 31 controls participated in this case-control study. Participants with CAI performed a 8-week home-based balance training, including 3 sessions a week. As main outcome measure, postural control was quantified after a vertical drop by means of the dynamic postural stability index (DPSI). Perceptual outcomes were documented using the FADI, FADI-Sport and VAS scales.

Results: At baseline, subjects with CAI displayed higher anterior/posterior and vertical postural instability, a poorer DPSI, and lower subjective stability scores compared to the control group. After balance training, all subjective stability scores improved significantly, although no changes were noted for the stability indices.

Conclusion: Subjects with CAI have an impaired postural control. As a treatment modality, balance training exhibits the capability of improving the subjective feeling of instability in subjects with CAI. However, there was no effect on dynamic postural control. Further research on the explanatory mechanisms of balance training is warranted and other training modalities should be considered.

Introduction

Chronic ankle instability (CAI) is a frequently reported residual outcome after an acute ankle sprain³⁸. CAI can be defined as the repetitive occurrence of instability and key characteristics are the presence of feelings of giving way and sustaining repetitive ankle sprains.¹⁶ CAI affects the functional performance level²⁰ and can lead in the long run to articular degenerative pathologies such as osteoarthritis.³⁵ Due to the unclear multifactorial pathogenesis including both peripheral and central mechanisms¹⁵, it imposes a great challenge for clinicians to tailor an adequate rehabilitation program for patients with CAI.

Impaired postural control has been repeatedly demonstrated in subjects with CAI^{1, 28}, and is believed to be the result of a combination of deficits in proprioception and neuromuscular control.¹⁶ A literature review on CAI indicated that studies using dynamic assessments were more consistent than static assessments at identifying deficits in postural control.¹⁷ Dynamic postural control has been defined as maintaining balance while transitioning from a dynamic to a static state, e.g. during a landing task.⁹ Various studies, evaluating ground reaction forces for calculating time-to-stabilization³⁰ and the dynamic postural stability index (DPSI)⁴⁵, have established the presence of dynamic postural control deficits in CAI.^{4, 29, 30, 42, 43} Therefore, improving dynamic postural control is considered an important goal in the treatment of CAI.

Balance training is a universally accepted rehabilitation modality for the treatment of acute ankle sprains and CAI, as well as a preventative intervention to reduce the risk of sustaining an ankle sprain.^{4, 18, 36, 39} Taube et al. attribute the effect of balance training to supraspinal adaptations leading to improved sensorimotor control.³⁴ Although the results of individual studies on the effect of balance training on postural control in subjects with CAI appear inconsistent,^{2, 8, 25, 31} a recent meta-analysis by Wikstrom et al. did indicate improvement after balance training.⁴¹ Differences in balance training protocols, but also the evaluated postural control parameters might explain these inconsistencies between the individual studies. Previous studies on CAI evaluated outcome effects on postural control using static measurements^{2, 8, 12, 13, 21, 25, 27, 31, 33} or dynamic measurements by means of the Star Excursion Balance Test (SEBT).^{12, 25, 33} Recently, a study including healthy subjects evaluated the effect of balance training on dynamic postural stability during a landing task.⁶ However, no studies, to the author's knowledge, have evaluated the effect of balance training on postural control during dynamic landing tasks in subjects with CAI, although most ankle sprains occur during sports including landing tasks.⁷

The aim of our study was twofold. First of all, the baseline presence of impaired dynamic postural control and self-reported functional disability in subjects with CAI was assessed by comparison

to a healthy control group. Secondly, the effect of a home-based 8-week balance training program in subjects with CAI on dynamic postural control during a landing task was evaluated. Secondary outcome measures were subjective ankle disability using the Foot and Ankle Disability Index (FADI) and its Sports subscale (FADI-S), and visual analogue scale (VAS) scores for perceived difficulty and instability. Our hypothesis was that both dynamic postural control and subjective scale scores would be worse at baseline in subjects with CAI compared to controls, and that a balance training program improves both objective and subjective parameters in subjects with CAI. Figure 1 visualizes the study comparisons to address these research questions.

Methods

Population

A total of 74 participants, including 43 subjects with CAI (age: 22.3 ± 3.2 yrs; height: 176.2 ± 8.9 cm; weight: 71.9 ± 12.2 kg; BMI: 23.1 ± 3.4) and 31 controls (age: 25.8 ± 2.0 yrs; height: 174.0 ± 9.6 cm; weight: 66.7 ± 9.7 kg; BMI: 21.9 ± 1.8), were recruited for this study. Inclusion in the CAI group was defined by the accumulation of all of the following criteria: multiple ankle sprains (two or more) with a history of at least one ankle sprain associated with pain, swelling, and stiffness resulting in a minimum of 3 weeks prohibition for participating in sport, recreational or other activities; feeling of weakness around the ankle; giving way; and a decreased functional participation (recreational, competitive or professionally) caused by the ankle sprains. Subjects with CAI were excluded if they had sustained an ankle sprain within the last three months prior to testing. The subjects in the control group had no history of a musculoskeletal lower leg injury in the last two years. Subjects of both groups were between 18-30 yrs and recreationally active, defined by at least 1.5 hours of cardiovascular activity per week. Overall exclusion criteria were lower limb pain, an ankle fracture or surgery and equilibrium deficits. This study was performed according to international ethical standards and approved by the Ghent University ethics committee.¹⁴ All subjects signed the informed consent.

Baseline measurements

Registration of anthropometric characteristics, completion of a medical history questionnaire and the Foot and Ankle Disability Index (FADI) and its sport subscale (FADI-S) took place at the beginning of the experimental procedure to determine baseline characteristics and functionality. Two visual analogue

scales (VAS) documenting perceived difficulty and feelings of instability during the testing protocol were filled out by the subjects with CAI prior to and after the balance training program. In case CAI subjects had bilateral instability, the most unstable ankle was tested, based on the medical history. The side allocation was randomized in the control subjects.

Subjects had to perform a barefooted unilateral vertical drop landing task and maintain balance during the post-landing period. They had to step down from a 40cm high box to control drop height and land onto the force plate. The force plate (AMTI, Watertown, Massachusetts) was embedded in the landing zone and captured kinetic data at 500Hz. A minimum of three practice trials were performed to familiarize subjects with the testing procedure. Subjects were asked to look straight forward and to keep both hands on the hips throughout the whole trial. Trials were discarded if the subject jumped from the box, if hands were removed from the hips to restore balance, if contact occurred between both legs to keep balance, if the foot after landing shifted, or if the contralateral foot made contact with the ground. Subjects were asked to keep their balance for at least 3 seconds after landing. The procedure was repeated until 5 usable trials were recorded. None of the participants reported discomfort during the landing task.

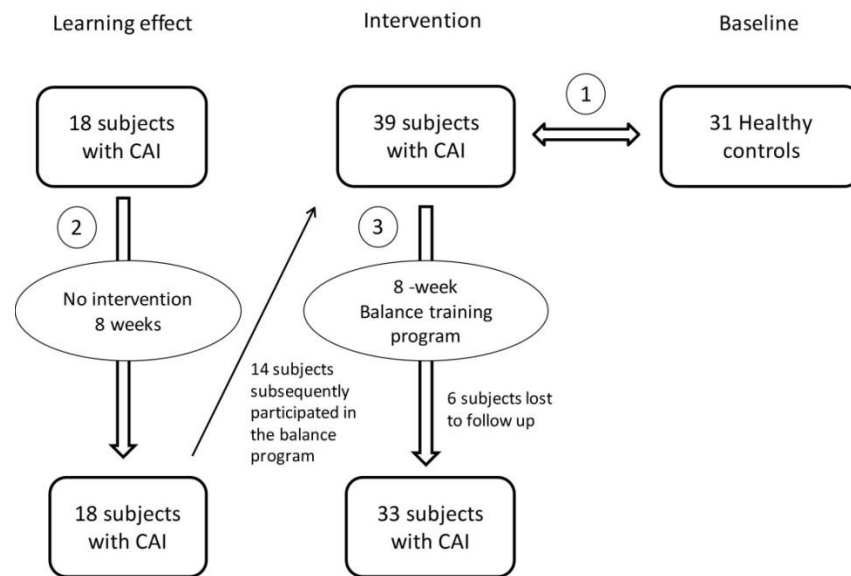


Figure 1. Flowchart visualizing study design. Numbers 1 to 3 indicate the performed study comparisons.

Balance training

As a reference group for the intervention, the first 18 subjects with CAI (age: 20.9 ± 2.3 yrs, height: 175.3 ± 9.2 cm, weight: 74.1 ± 11.4 kg, BMI: 24.2 ± 3.9 , FADI: 89 ± 6.8 , FADI-S: 69.8 ± 10.3 ; no significant differences with the actual intervention group) initially received no balance training after baseline

measurements. This allowed to evaluate the possible presence of a learning effect by performing the landing protocol and to evaluate the effect of time on study variables. After 8 weeks, similar to the duration of the training program, they were screened for the same study variables. Subsequently, 14 of them (part of the 39 in total) agreed to perform the balance program (Fig. 1).

Table 1. Balance program exercise and progression scheme

A. Balance program exercises								
A. Single leg stance:				D. Heel raise:				
1. Firm surface, EO, arms crossed				1. Firm surface, EO, bilateral				
2. Firm surface, EC, arms free				2. Firm surface, EO, unilateral				
3. Firm surface, EC, arms crossed								
4. Airex, EO, arms crossed				E. Lunge/jump exercise:				
5. Airex, EC, arms free				1. Firm surface, EO, forward, distance 45 cm				
6. Airex, EC, arms crossed				2. Firm surface, EO, forward + sideways, distance 45cm				
7. Balance Board, EO, arms free				3. Firm surface, EO, forward + sideways, distance 70 cm				
8. Balance Board, EO, arms free, rotating the board				4. Airex, EO, forward + sideways, distance 45 cm				
B. Crossed leg sway:				F. Double leg stance:				
1. Firm surface, EO, hands on the hips				1. Balance Board, EO				
2. Airex, EO, hands on the hips				2. Balance Board, EO, rotating the board				
3. Airex, EC, arms free				3. Balance Board, EC				
4. Airex, EC, hands on the hips				4. Balance Board, EC, rotating the board				
C. Single leg squat:				G. Drop jump:				
1. Firm surface, EO, hands on the hips				1. Firm surface, EO				
2. Firm surface, EC, hands on the hips				2. Airex, EO				
3. Airex, EO, hands on the hips								
4. Airex, EC, hands on the hips								
B. Balance program progression scheme								
Exercise	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8
A	1	2	3 + 4	3 + 4	5 + 7	5 + 7	6 + 8	6 + 8
B	1	1	1	2	2	3	3	4
C	1	1	2	2	3	3	4	4
D	1	1	1	2	2	2	2	2
E		1	2	2	3	3	4	4
F			1	1	2	2	3	4
G					1	1	2	2

EO=eyes open; EC=eyes closed.

Eventually, 39 subjects with CAI performed a progressive home-based, unsupervised balance training program during 8 weeks. The included exercises and progression scheme are provided in table 1, a more

detailed description can be found in supplemental file 1. Almost all exercises were performed unilaterally (tested ankle) and progression consisted of variation in arm position, visual control and surface material.²² Included exercises were adapted from existing balance protocols proven effective in reducing ankle sprain incidence and residual complaints, and improving postural control.^{12, 18, 37, 40} Subjects had to perform these balance exercises 3 times a week, bringing the total at 24 balance sessions. At the beginning of the training period, the exercises were explained and all received an instruction booklet in which all exercises were documented per session. Every subject received a foam pad (Airex AG, Sins, Switzerland) and a wobble board (Physio Supplies LTD, Lincolnshire, United Kingdom)^a. In addition, a DVD was provided containing movies of all 24 complete balance sessions, so that subjects could perform the exercises under verbal guidance and with visual demonstration. To document the compliance and possible comments, subjects had to fill out a diary. In addition, telephone follow up was done by a member of the research group on a weekly basis. Based on subject's feedback, progression of the exercises was performed as documented or individually adapted for exercises raising difficulty. Subjects who were compliant with the training program, i.e. not missing more than 20% (5 sessions) of all training sessions, completed the FADI and FADI-S, and performed the vertical drop (and VAS) once again after completion of the training program.

Data analysis

All force data were processed using Matlab. All data were filtered using a fourth order Butterworth low-pass filter 15Hz. The modified dynamic postural stability index (DPSI) and its directional stability indices for the first 3 seconds after landing, i.e. anterior/posterior (APSI), mediolateral (MLSI) and vertical stability index (VSI), were calculated as described by Wikstrom et al.⁴⁴ For all these indices, a higher value is associated with poorer postural control.

Statistical analysis was performed in SPSS 21 (SPSS Inc., Chicago, Illinois 60606, U.S.A.). Study variables were divided into two main constructs, i.e. postural stability measures (DPSI and its directional subcomponents) and subjective self-reported measures (FADI, FADI-S and VAS scales). For baseline analysis between the healthy controls and the subjects with CAI, a multivariate analysis of variance (MANOVA) was performed evaluating the main effect of the study group on the two determined constructs. If the main effect was significant, an independent Student's t-test was performed on the individual variables to identify specific group differences. For the intervention analysis, i.e. for the subjects with CAI that performed the balance program, a multivariate analysis of variance for repeated measures was performed to evaluate the main effect of the intervention on the two constructs. When a

significant main effect of the intervention was established, paired samples t-tests were performed on the individual variables to identify specific intervention outcomes. To evaluate the learning effect in the subject group with CAI who did not initially perform the balance program, paired samples t-tests were performed on every individual parameter. The significant alpha level was set at 0.05.

Results

Baseline measurements

No significant anthropometric differences ($p>0.05$) were found between the subjects with CAI and the control group for weight (resp. $71.9\pm 12.2\text{kg}$ and $66.7\pm 9.7\text{kg}$), height (resp. $176.2 \pm 8.9\text{cm}$ and $174.0\pm 9.6\text{cm}$) and BMI (resp. 23.1 ± 3.4) and 22.0 ± 1.6). Subjects with CAI were significantly younger ($22.3\pm 3.2\text{yrs}$) than the control group ($25.8\pm 2.0\text{yrs}$) ($p<0.001$).

Table 2 shows the study results for the postural control and self-reported outcome measures for the healthy controls versus the subjects with CAI. Results indicated a significant main effect of study group on both postural stability ($p=0.004$) and self-reported outcome measures ($p<0.001$). Further analysis revealed a significantly lower score, i.e. higher disability, in subjects with CAI for both the FADI and the FADI-s compared to the control group ($p<0.001$). The postural stability outcome measures demonstrated post hoc significantly higher instability scores for the APSI ($p=0.002$), VSI ($p=0.001$) and DPSI ($p=0.001$). The MLSI was not significantly different between the healthy control group and the subjects with CAI ($p=0.228$).

Table 2. Baseline comparison

	CON (n=31)	CAI (n=39)	Mean diff [95% CI]	P-value	Effect size
FADI	100 (0)*	87.2(8.7)*	-12.84 [-15.95, -9.73]	<0.001*	2.00
FADI-S	100 (0)*	70.4(10.7)*	-29.47 [-33.33, -25.62]	<0.001*	3.76
APSI	0.102 (0.010)	0.109 (0.009)	-0.007 [-0.012, -0.003]	0.002*	0.75
MLSI	0.022 (0.005)	0.023 (0.004)	-0.001 [-0.004, 0.001]	0.190	0.23
VSI	0.262 (0.040)	0.296 (0.038)	-0.034 [-0.053, -0.015]	0.001*	0.89
DPSI	0.284 (0.037)	0.316 (0.036)	-0.033 [-0.050, -0.015]	<0.001*	0.89

Mean diff=Mean difference; CI=Confidence interval); * indicates significant differences between CON and CAI ($p\leq 0.05$). Effect size was calculated using Cohen's d.

Balance training

The 18 subjects with CAI who initially performed no balance training to establish the possible presence of a learning effect, exhibited no significant differences between the 2 baseline screening moments before and after the 8 week time interval for both FADI and FADI-S, and for the stability indices (FADI resp. 89.1±6.8% and 90±4.5%, p=0.488; FADI-S: resp. 69.8±10.3% and 73.2±11.5%, p=0.255; APSI: resp. 0.108±0.009 and 0.110±0.012, p=0.274; MLSI: resp. 0.024±0.004 and 0.024±0.004, p=0.669; VSI: resp. 0.286±0.027 and 0.289±0.028, p=0.421; DPSI: resp. 0.306±0.026 and 0.311±0.027, p=0.347).

Of the 39 subjects who started the balance training, two female and three male subjects dropped out (one due to inflammation; one sustained a severe ankle sprain during track training; and three ended participation due to lack of motivation to complete the program). One female subject missed 6 balance sessions, exceeding the 5 session limit. Therefore, 33 subjects (16 males and 17 females) successfully completed the balance training program. Overall, the total number of sessions completed was 23.43 ± 1.12, with the number of training sessions missed ranging from 0-5.

Balance training resulted in significant improvements in self-reported function but not in dynamic postural stability (table 3). After balance training, subjects with CAI reported a significant decrease in subjective disability determined by the FADI (p=0.001) and FADI-S (p=0.005). In addition, VAS score indicated a significant decrease (p<0.001) in perceived difficulty level of and feelings of instability during the testing protocol. Table 3 shows the study results for the postural control and self-reported outcome measures of the subjects with CAI prior to and after the balance training protocol.

Table 3. Treatment outcome

	CAI Pre (n=33)	CAI Post (n=33)	Mean diff [95% CI]	P-value	Effect size
FADI	87.2 (8.4)	92.44 (6.9)	-5.21 [-8.25, -2.19]	0.001*	0.68
FADI-S	71.4 (11.7)	78.0 (13.7)	-6.59 [-11.04, -2.15]	0.005*	0.52
VAS Diff lev (mm)	37.8 (23.6)	13.4 (14.9)	24.36 [16.59, 32.14]	<0.001*	1.24
VAS PI (mm)	47.5 (25.2)	13.4 (12.7)	33.70 [24.54, 42.86]	<0.001*	1.71
APSI	0.109 (0.010)	0.108 (0.010)	0.001 [-0.003,0.005]	NS	0.10
MLSI	0.023 (0.004)	0.024 (0.004)	-0.001 [-0.002, 0.0002]	NS	0.25
VSI	0.297 (0.040)	0.291 (0.036)	0.006 [-0.005, 0.017]	NS	0.16
DPSI	0.318 (0.038)	0.312 (0.035)	0.006 [-0.005, 0.017]	NS	0.16

CAI Pre=subjects with chronic ankle instability prior to the balance training program; CAI Post=subjects with chronic ankle instability after the balance training program; Diff lev=difficulty level; PI=perceived instability. Significant paired samples t-test are indicated with *(p≤0.05). NS signifies the absence of a main effect of the intervention on the postural stability measures (repeated measures ANOVA), which are therefore not further explored. Effect size was calculated using Cohen's d.

Discussion

Our study was the first to evaluate the effect of a home-based balance training program on the postural control during a dynamic landing task in subjects with CAI. Baseline comparison showed that subjects with CAI did in fact have an impaired postural control. Our hypothesis on the improvement after the balance training program was only partially confirmed. Subjective parameters evaluating ankle function improved significantly in subjects with CAI. However, stability indices calculated by means of the DPSI or its directional components, did not improve. Therefore, our balance program failed to induce changes in postural control during dynamic landing performance.

Despite some inconsistencies in the literature, a recent meta-analysis showed that CAI can be associated with impaired postural control.^{1, 26, 41} Our study results confirmed this assumption for a dynamic functional landing task. At baseline, our study results showed that our subjects with CAI had a significantly higher APSI, VSI and DPSI compared to the control group. These findings are in line with previous studies.^{43, 44} The poorer anterior/posterior stability has also been confirmed by studies using time-to-stabilization calculations.^{4, 29, 30} As a possible explanation, Ross and Guskiewicz hypothesized that CAI, associated with mechanisms such as decreased proprioception, reflex stabilization and neuromuscular control, causes larger center of mass oscillations approaching the limits of stability. This would result in a longer time to decelerate these center of mass oscillations.²⁹ On the other hand, in a study of Wikstrom et al. similar findings were found for a coper group versus control group questioning the above as a mechanism attributed to CAI.⁴⁴ Concerning MLSI, inconsistent findings are portrayed in literature. We found no difference in this frontal plane index in accordance with several studies.^{3, 4, 43, 44} Explanatory theories, as a lack of compensation strategy⁴⁴, remain hypothetical and the inconsistencies as yet unclear. In conclusion, our results reveal the presence of an impaired postural control in our group of subjects with CAI, which was an important baseline characteristic for our intervention study.

The results of our 8-week balance training program revealed a significant improvement in perceived functionality (FADI and FADI-S) and difficulty/instability level (VAS) during the landing task, whereas for the subjects who initially did not perform the intervention no differences were found. The FADI is developed to assess every day activities and the FADI-S assesses more difficult sport-related tasks. A reliability and sensitivity study by Hale and Hertel showed that these questionnaires are reliable in establishing functional limitations in subjects with CAI and are responsive to improvements in function after rehabilitation¹¹, These findings on subjective improvement are consistent with other intervention studies.^{12, 25, 31} It can be concluded that an 8-week balance training protocol improves self-reported

functionality in subjects with CAI. This can be considered an important treatment effect which should not be underestimated because the perception of a patient or athlete may very well influence the effectiveness of the treatment modality in preventing injury.³² However, caution is warranted. After all, the balance protocol showed no effect on the dynamic postural control measured by means of the DPSI. More confidence in ability combined with impaired postural control might increase susceptibility to injury.

Our hypothesis that a home-based balance training program would improve postural control could not be confirmed. We found that the DPSI and its directional sub-component indices did not change after the balance training program. Although literature reviews have stated that the currently available evidence is insufficient to make a definitive conclusion on the effect of balance training on postural control in subjects with CAI,^{24, 39} Wikstrom et al. did find evidence for a positive effect in their recent meta-analysis.⁴¹ This positive effect was, however, not confirmed by our study results. Most of these available studies evaluated static postural control by means of a force plate.^{13, 19, 21} McKeon et al. argued that there may be a lack of sensitivity to detect differences between subjects with CAI and healthy controls²³ and to detect improvements²⁴ using these postural control measures. Only 3 studies demonstrated the effect of balance training on dynamic postural in subjects with CAI, using the SEBT.^{12, 25, 33} They found higher reaching distances after balance training, but directions of improvement were not consistent between studies. Furthermore, this clinical test does not represent a functional landing movement in every day living or sport situations. In our study, we assessed postural control during a dynamic landing task. Nevertheless, no improvements were detected after our 8-week home-based balance training program during a functional landing task using DPSI as a parameter. A possible explanation might be that the used balance training program was not specific enough to enhance postural control during the performed dynamic tasks. The 8-week home-based balance training program used in the current study is based on progression in difficulty level of the included exercises. We integrated single leg stance and dynamic balance exercises with traditional progression by means of visual control, surface material and variation in arm position.²² Due to the high variety of balance programs, the exercises of our program slightly differed from those used in other investigations on CAI.^{2, 5, 33} In addition, duration of these balance programs varied substantially compared to which ours was rather long. Overall, our program included mainly static exercises, gradually increasing in difficulty. After 2 weeks, subjects started to perform balance exercises during dynamic tasks. However, the training program might be not sufficiently specific to improve postural balance during the investigated landing tasks. This was also assumed by Fitzgerald et al., who found no improvement of the DPSI during a landing

task after a static double and single leg stance balance protocol in healthy subjects.⁶ Possibly, more specific dynamic exercises are needed to obtain a significant training effect. Until now, it remains unclear which exercises best serve the rehabilitation purposes in the treatment of subjects with CAI. In conclusion, our home-based treatment protocol did not improve postural control using DPSI measured during a vertical drop. Research using other outcome parameters for dynamic postural control and other functional tasks are necessary to make a general statement on the effect of balance training on dynamic postural control. In addition, since ankle sprains frequently occur during landing tasks, more studies comparing other interventions, e.g. landing technique training, are warranted to evaluate treatment outcome.

Limitations

Possible limitations of the current study have to be borne in mind. First of all, the balance training program was not performed under supervision as we included only home-based exercises. This reflects, on the other hand, a real treatment situation as patients often receive home-based exercises. A study of Hupperets et al. has shown the capability of unsupervised home-based exercises to reduce ankle sprain incidence.¹⁸ To stimulate compliance and adequate performance of the exercises, a DVD was provided to perform the program under visual guidance in addition to a booklet explaining different exercises. Compliance was monitored by telephonic follow up and diaries. Regarding the subjective scales, the VAS scores were only registered for the balance group and not for the control groups, inhibiting base line comparison and entailing cautious interpretation. Furthermore, combining lower limb kinematics with ground reaction forces could provide better insight in landing mechanisms and postural control strategies. Finally, our inclusion criteria were set before the recent position statement by the International Ankle Consortium.¹⁰ We believe our criteria to be to a large extent in line with the position statement as we included subjects with (1) a significant ankle sprain, (2) presence of episodes of 'giving way', repetitive sprains, and feelings of instability, and we used (3) a self-reported function scale (FADI).

Conclusion

As a treatment modality, balance training exhibits the capability of improving the subjective feeling of instability in subjects with CAI. These results encourage implementation in the overall rehabilitation program for chronic ankle instability. However, our home-based balance training protocol had no effect on dynamic postural control by means of DPSI during a vertical drop.

References

- (1) Arnold BL, De La Motte S, Linens S, Ross SE. Ankle instability is associated with balance impairments: a meta-analysis. *Med Sci Sports Exerc* 2009;41(5):1048-1062.
- (2) Bernier JN, Perrin DH. Effect of coordination training on proprioception of the functionally unstable ankle. *J Orthop Sports Phys Ther* 1998;27(4):264-275.
- (3) Brown CN, Bowser B, Orellana A. Dynamic postural stability in females with chronic ankle instability. *Med Sci Sports Exerc* 2010;42(12):2258-2263.
- (4) Brown CN, Mynark R. Balance deficits in recreational athletes with chronic ankle instability. *J Athl Train* 2007;42(3):367-373.
- (5) Eils E, Rosenbaum D. A multi-station proprioceptive exercise program in patients with ankle instability. *Med Sci Sports Exerc* 2001;33(12):1991-1998.
- (6) Fitzgerald D, Trakarnratanakul N, Smyth B, Caulfield B. Effects of a wobble board-based therapeutic exergaming system for balance training on dynamic postural stability and intrinsic motivation levels. *J Orthop Sports Phys Ther* 2010;40(1):11-19.
- (7) Fong DT, Hong Y, Chan LK, Yung PS, Chan KM. A systematic review on ankle injury and ankle sprain in sports. *Sports Med* 2007;37(1):73-94.
- (8) Gauffin H, Tropp H, Odenrick P. Effect of ankle disk training on postural control in patients with functional instability of the ankle joint. *Int J Sports Med* 1988;9(2):141-144.
- (9) Goldie PA, Bach TM, Evans OM. Force platform measures for evaluating postural control: reliability and validity. *Arch Phys Med Rehabil* 1989;70(7):510-517.
- (10) Gribble PA, Delahunt E, Bleakley C et al. Selection criteria for patients with chronic ankle instability in controlled research: a position statement of the international ankle consortium. *J Orthop Sports Phys Ther* 2013;43(8):585-591.
- (11) Hale SA, Hertel J. Reliability and Sensitivity of the Foot and Ankle Disability Index in Subjects With Chronic Ankle Instability. *J Athl Train* 2005;40(1):35-40.
- (12) Hale SA, Hertel J, Olmsted-Kramer LC. The effect of a 4-week comprehensive rehabilitation program on postural control and lower extremity function in individuals with chronic ankle instability. *J Orthop Sports Phys Ther* 2007;37(6):303-311.
- (13) Han K, Ricard MD, Fellingham GW. Effects of a 4-week exercise program on balance using elastic tubing as a perturbation force for individuals with a history of ankle sprains. *J Orthop Sports Phys Ther* 2009;39(4):246-255.
- (14) Harriss DJ, Atkinson G. Ethical standards in sport and exercise science research: 2014 update. *Int J Sports Med* 2013;34(12):1025-1028.
- (15) Hass CJ, Bishop MD, Doidge D, Wikstrom EA. Chronic ankle instability alters central organization of movement. *Am J Sports Med* 2010;38(4):829-834.
- (16) Hertel J. Functional Anatomy, Pathomechanics, and Pathophysiology of Lateral Ankle Instability. *J Athl Train* 2002;37(4):364-375.
- (17) Hertel J. Sensorimotor deficits with ankle sprains and chronic ankle instability. *Clin Sports Med* 2008;27(3):353-70, vii.

- (18) Hupperets MD, Verhagen EA, van MW. Effect of unsupervised home based proprioceptive training on recurrences of ankle sprain: randomised controlled trial. *BMJ* 2009;339:b2684.
- (19) Kidgell DJ, Horvath DM, Jackson BM, Seymour PJ. Effect of six weeks of dura disc and mini-trampoline balance training on postural sway in athletes with functional ankle instability. *J Strength Cond Res* 2007;21(2):466-469.
- (20) Konradsen L, Bech L, Ehrenbjerg M, Nickelsen T. Seven years follow-up after ankle inversion trauma. *Scand J Med Sci Sports* 2002;12(3):129-135.
- (21) Matsusaka N, Yokoyama S, Tsurusaki T, Inokuchi S, Okita M. Effect of ankle disk training combined with tactile stimulation to the leg and foot on functional instability of the ankle. *Am J Sports Med* 2001;29(1):25-30.
- (22) Mattacola CG, Dwyer MK. Rehabilitation of the Ankle After Acute Sprain or Chronic Instability. *J Athl Train* 2002;37(4):413-429.
- (23) McKeon PO, Hertel J. Systematic review of postural control and lateral ankle instability, part I: can deficits be detected with instrumented testing. *J Athl Train* 2008;43(3):293-304.
- (24) McKeon PO, Hertel J. Systematic review of postural control and lateral ankle instability, part II: is balance training clinically effective? *J Athl Train* 2008;43(3):305-315.
- (25) McKeon PO, Ingersoll CD, Kerrigan DC, Saliba E, Bennett BC, Hertel J. Balance training improves function and postural control in those with chronic ankle instability. *Med Sci Sports Exerc* 2008;40(10):1810-1819.
- (26) Munn J, Sullivan SJ, Schneiders AG. Evidence of sensorimotor deficits in functional ankle instability: a systematic review with meta-analysis. *J Sci Med Sport* 2010;13(1):2-12.
- (27) O'Driscoll J, Delahunt E. Neuromuscular training to enhance sensorimotor and functional deficits in subjects with chronic ankle instability: A systematic review and best evidence synthesis. *Sports Med Arthrosc Rehabil Ther Technol* 2011;3:19.
- (28) Riemann BL. Is There a Link Between Chronic Ankle Instability and Postural Instability? *J Athl Train* 2002;37(4):386-393.
- (29) Ross SE, Guskiewicz KM. Examination of static and dynamic postural stability in individuals with functionally stable and unstable ankles. *Clin J Sport Med* 2004;14(6):332-338.
- (30) Ross SE, Guskiewicz KM, Yu B. Single-leg jump-landing stabilization times in subjects with functionally unstable ankles. *J Athl Train* 2005;40(4):298-304.
- (31) Rozzi SL, Lephart SM, Sterner R, Kuligowski L. Balance training for persons with functionally unstable ankles. *J Orthop Sports Phys Ther* 1999;29(8):478-486.
- (32) Sawkins K, Refshauge K, Kilbreath S, Raymond J. The placebo effect of ankle taping in ankle instability. *Med Sci Sports Exerc* 2007;39(5):781-787.
- (33) Sefton JM, Yarar C, Hicks-Little CA, Berry JW, Cordova ML. Six weeks of balance training improves sensorimotor function in individuals with chronic ankle instability. *J Orthop Sports Phys Ther* 2011;41(2):81-89.
- (34) Taube W, Gruber M, Gollhofer A. Spinal and supraspinal adaptations associated with balance training and their functional relevance. *Acta Physiol (Oxf)* 2008;193(2):101-116.
- (35) Valderrabano V, Hintermann B, Horisberger M, Fung TS. Ligamentous posttraumatic ankle osteoarthritis. *Am J Sports Med* 2006;34(4):612-620.

- (36) van der Wees PJ, Lenssen AF, Hendriks EJ, Stomp DJ, Dekker J, de Bie RA. Effectiveness of exercise therapy and manual mobilisation in ankle sprain and functional instability: a systematic review. *Aust J Physiother* 2006;52(1):27-37.
- (37) Verhagen E, van der Beek A, Twisk J, Bouter L, Bahr R, van Mechelen W. The effect of a proprioceptive balance board training program for the prevention of ankle sprains: a prospective controlled trial. *Am J Sports Med* 2004;32(6):1385-1393.
- (38) Verhagen RA, de Keizer G, van Dijk CN. Long-term follow-up of inversion trauma of the ankle. *Arch Orthop Trauma Surg* 1995;114(2):92-96.
- (39) Webster KA, Gribble PA. Functional rehabilitation interventions for chronic ankle instability: a systematic review. *J Sport Rehabil* 2010;19(1):98-114.
- (40) Wester JU, Jespersen SM, Nielsen KD, Neumann L. Wobble board training after partial sprains of the lateral ligaments of the ankle: a prospective randomized study. *J Orthop Sports Phys Ther* 1996;23(5):332-336.
- (41) Wikstrom EA, Naik S, Lodha N, Cauraugh JH. Balance capabilities after lateral ankle trauma and intervention: a meta-analysis. *Med Sci Sports Exerc* 2009;41(6):1287-1295.
- (42) Wikstrom EA, Tillman MD, Borsa PA. Detection of dynamic stability deficits in subjects with functional ankle instability. *Med Sci Sports Exerc* 2005;37(2):169-175.
- (43) Wikstrom EA, Tillman MD, Chmielewski TL, Cauraugh JH, Borsa PA. Dynamic postural stability deficits in subjects with self-reported ankle instability. *Med Sci Sports Exerc* 2007;39(3):397-402.
- (44) Wikstrom EA, Tillman MD, Chmielewski TL, Cauraugh JH, Naugle KE, Borsa PA. Dynamic postural control but not mechanical stability differs among those with and without chronic ankle instability. *Scand J Med Sci Sports* 2010;20(1):e137-e144.
- (45) Wikstrom EA, Tillman MD, Smith AN, Borsa PA. A new force-plate technology measure of dynamic postural stability: the dynamic postural stability index. *J Athl Train* 2005;40(4):305-309.

Supplemental file 1. The 8-week balance training program

Week		exercise	surface	open	modality	comments
1	A	single leg stance	firm	open	3 x 20"	Arms across the chest
	B	crossed leg sway	firm	open	3 x 20"	Hands on the pelvis
	C	single leg squat	firm	open	2 x 10	Hands on the pelvis, squat between 30° en 45°
	D	heel raise	firm	open	2 x 20	Bilateral
2	A	single leg stance	firm	closed	3 x 20"	Arms may be used for balance
	B	crossed leg sway	firm	open	3 x 20"	Hands on the pelvis
	C	single leg squat	firm	open	3 x 10	Hands on the pelvis
	D	heel raise	firm	open	2 x 10	Bilateral
	E	lung/jump exercise	firm	open	2 x 10	45 cm distance, hands on the pelvis, forward
3	A	single leg stance	foam pad	open	3 x 20"	Arms across the chest
	A	single leg stance	firm	closed	3 x 20"	Arms across the chest
	B	crossed leg sway	firm	open	3 x 20"	Hands on the pelvis
	C	single leg squat	firm	closed	2 x 10	Hands on the pelvis
	D	heel raise	firm	open	2 x 20	Bilateral
	E	lung/jump exercise	firm	open	2 x 10	45 cm distance, hands on the pelvis, forward and sideways
	F	double leg stance	balance board	open	3 x 20"	Hands on the pelvis
4	A	single leg stance	foam pad	open	3 x 30"	Arms across the chest
	A	single leg stance	firm	closed	3 x 20"	Arms can be used for balance
	B	crossed leg sway	foam pad	open	3 x 20"	Hands on the pelvis
	C	single leg squat	firm	closed	2 x 10	Hands on the pelvis
	D	heel raise	firm	open	2 x 10	Unilateral
	E	lung/jump exercise	firm	open	2 x 10	45 cm distance, hands on the pelvis, forward and sideways
	F	double leg stance	balance board	open	3 x 20"	Hands on the pelvis
5	A	single leg stance	foam pad	closed	3 x 20"	Arms can be used for balance
	A	single leg stance	balance board	open	3 x 20"	Arms can be used for balance
	B	crossed leg sway	foam pad	open	3 x 20"	Hands on the pelvis
	C	single leg squat	foam pad	open	2 x 10	Hands on the pelvis
	D	heel raise	firm	open	2 x 10	Unilateral
	E	lung/jump exercise	firm	open	2 x 10	70 cm distance, hands on the pelvis, forwards and sideways
	F	double leg stance	balance board	open	3 x 20"	Hands on the pelvis
	G	Vertical drop	firm	open	2 x 10	Hands on the pelvis
6	A	single leg stance	foam pad	closed	3 x 20"	Arms can be used for balance
	A	single leg stance	balance board	open	3 x 20"	Arms can be used for balance
	B	crossed leg sway	foam pad	closed	3 x 20"	Hands on the pelvis
	C	single leg squat	foam pad	open	3 x 10	Hands on the pelvis
	D	heel raise	firm	open	2 x 10	Unilateral
	E	lung/jump exercise	firm	open	2 x 10	70 cm distance, hands on the pelvis, forward and sideways

	F	double leg stance	balance board	open	3 x 20"	Rotate balance board, hands on the pelvis
	G	drop jump	firm	open	2 x 10	Hands on the pelvis
7	A	single leg stance	foam pad	closed	3 x 20"	Arms across the chest
	A	single leg stance	balance board	open	3 x 20"	Rotate balance board, hands on the pelvis
	B	crossed leg sway	airex	closed	3 x 20"	Hands on the pelvis
	C	single leg squat	airex	closed	2 x 10	Hands on the pelvis
	D	heel raise	vlak	open	2 x 10	Unilateral 45 cm distance, hands on the pelvis, forward and sideways
	E	lung/jump exercise	foam pad	open	2 x 10	sideways
	F	double leg stance	balance board	closed	3 x 20"	Hands on the pelvis
	G	Vertical drop	foam pad	open	2 x 10	Hands on the pelvis
8	A	single leg stance	foam pad	closed	3 x 20"	Arms across the chest
	A	single leg stance	balance board	open	3 x 20"	Rotate balance board, hands on the pelvis
	B	crossed leg sway	foam pad	closed	3 x 20"	Hands on the pelvis
	C	single leg squat	foam pad	closed	2 x 10	Hands on the pelvis
	D	heel raise	foam pad	open	2 x 10	Unilateral 45 cm distance, hands on the pelvis, forward and sideways
	E	lung/jump exercise	foam pad	open	2 x 10	sideways
	F	double leg stance	balance board	closed	3 x 20"	Rotate balance board, hands on the pelvis
	G	drop jump	foam pad	open	2 x 10	Hands on the pelvis

Effect of tape on dynamic postural stability in subjects with chronic ankle instability

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Abstract

Objective: The objective of our study was to evaluate the effect of taping on the dynamic postural stability during a jump landing protocol in subjects with chronic ankle instability (CAI).

Methods: 28 subjects with CAI performed a sagittal and frontal plane landing task while landing on one foot and maintaining balance in a non-tape and tape condition. The taping procedure consisted of a double 'figure of six' and a medial heel lock. The dynamic postural stability index (DPSI) and its directional components were calculated to objectify postural control. In addition, subjective feelings of instability and perceived difficulty level were assessed by means of visual analogue scales. The mechanical effectiveness of the used tape protocol on the ankle joint was determined by registering 3D kinematics during landing.

Results: The tape was effective in reducing the plantar flexion and inversion at the ankle at touchdown ($p < 0.05$). In general, range of motion in the post landing phase was decreased. There was, however, no significant effect on the DPSI nor on its directional subcomponents ($p > 0.05$). Subjective feelings of stability with tape improved significantly ($p < 0.05$), whereas perceived difficulty during the jump landing tasks did not change.

Conclusions: Our taping procedure did not improve postural control during a sagittal and frontal plane landing task in subjects with CAI, when measured through DPSI. Perceived instability did improve and is considered an important treatment outcome, which suggests that taping could be considered as a treatment modality by clinicians.

Introduction

Chronic ankle instability (CAI) is a frequently reported residual pathology as a result of an initial ankle sprain event. A recent prevalence study among high school and collegiate athletes identified CAI in 23.4% of all participants based on questionnaires.³⁶ The high prevalence of CAI is caused by an unclear multifactorial underlying mechanism, which complicates accurate treatment. Functional ankle instability has been attributed to a combination of deficits in proprioception, neuromuscular control, strength and postural control¹³. Different treatment protocols aim at improving these inadequacies by using a variety of exercise types (e.g. proprioceptive, balance, strength and functional training), but consensus is lacking.^{11, 23}

One of the above mentioned mechanisms associated with CAI is an impaired postural control. This impaired postural control has been repeatedly demonstrated in subjects with CAI¹ and is believed to be the result of a combination of impaired proprioception and neuromuscular control.¹³ In literature, studies on CAI have investigated both static and dynamic measures to evaluate postural control, but dynamic measures have been proven more consistent in identifying postural control deficits in subjects with CAI.¹⁴ This is in agreement with other authors, suggesting that functional tasks may be more sensitive and specific in identifying subjects with CAI than static single leg stance.^{30, 31} Dynamic postural control has been defined as maintaining balance while transitioning from a dynamic to a static state, which can be evaluated based on ground reaction forces.⁸ Results of these studies were found consistent in identifying postural control deficits in subjects with CAI.^{2, 3, 31, 32, 41, 42} In addition, based on the influence of jump direction on postural control measures, it has been underlined that multiple directions should be included to assess postural control.²⁰ As interplay between postural control and injury, it is believed that a more stable body results in a reduced incidence of recurrent lower extremity injuries emphasizing that improving postural control is an important aspect of injury prevention.³⁷ Therefore, improving postural control can be considered an important treatment goal in rehabilitation programs of subjects with CAI.

Tape is a frequently used treatment modality in subjects with CAI. Especially during sport activities in which higher demands are imposed on the ankle joint, athletes find support in the use of tape. Although, the precise preventative working mechanism of tape remains as of yet unclear, it has been proven to effectively reduce the incidence of ankle sprains.²¹ Next to limiting range of motion (ROM)³⁸, improvement of proprioceptive input by stimulation of cutaneous receptors has been hypothesized.⁴ A recent review by Raymond et al., however, refuted the effect of tape on

proprioception.²⁷ In addition, the assumed positive effect on postural control has not been confirmed in literature.^{5, 15} The studies that evaluated this effect of tape on postural control used unilateral stance protocols whether or not combined with a dynamic task (e.g. Star Excursion Balance Test).^{5, 15} To the author's knowledge, no studies have been done evaluating the effect of tape on postural control during a dynamic landing task even though this kind of task simulates a provocative event for sustaining an ankle sprain.

The goal of our study was to assess the effect of tape on postural control by means of the dynamic postural stability index during a sagittal and frontal plane landing task in subjects with CAI. Secondary outcome measures were visual analogue scale (VAS) scores for perceived difficulty and ankle instability during the landing tasks. Our null hypothesis is that both postural control and subjective scale scores would not change in the taped condition compared to the non-taped condition.

Methods

Population

Twenty-eight subjects with lateral chronic ankle instability (10 men and 18 women, age: 22.25±2.96yrs., height: 1.73±0.10m, weight: 70.97±10.60kg, BMI: 23.82±2.75, FADI: 88,20±7.18%; FADI-S: 69±9.56%) volunteered to participate in our repeated measure design. To be eligible, subjects had to meet all of the following inclusion criteria: a history of a severe ankle sprain resulting in prohibiting participation in sport, recreational or other activities for at least 3 weeks; episodes of giving way; repetitive ankle sprains; feelings of instability and weakness around the ankle joint; recreationally active defined by a minimum of 1,5 hours of cardiovascular activity a week. Exclusion criteria were ankle fracture or surgery, lower limb complaints at the moment of testing (not related to CAI), and equilibrium disorders. This study was performed according to international ethical standards and approved by the Ghent University ethics committee¹². All subjects signed the informed consent.

Tape

Before administering the 4cm wide, non-elastic Strappal[®] tape^a the skin was clean-shaven and covered with an adhesive spray (Tensospray[®] Hypoalleregenic spray, Scott Medical Ltd, Lisburn, Northern Ireland). To stabilize the ankle joint a double 'figure of 6' was applied and a single heel-lock (Fig. 1). The foot was held in a neutral 90° position throughout the taping procedure. The 'figure of 6' started on the

medial side of the foot on the navicular bone to the sole of the foot, going underneath the calcaneocuboid joint to the lateral side, and then up to the lower leg slightly anterior to the lateral malleolus over the anterior talofibular ligament complex. Then the tape crossed to the medial side around the tibia, completing a circular motion around the lower leg (Fig 1). This was then repeated a second time with a 3cm overlap. This tape restricted plantar flexion and supination of the hind foot. To control the pronation motion, a medial heel lock was used. The tape started on the anterior surface of the tibia going laterally above the lateral malleolus, over the insertion of the Achilles tendon and calcaneus to the medial side of the calcaneus. Then the tape went underneath the sole of the foot to the lateral edge to come back up and end on the dorsum of the foot (fig 1). A proximal and distal anchor was added to fixate the tape ends. The same researcher applied all tapes.



Figure 1. Taping protocol with double 'figure of 6' and medial heel lock (without distal anchor)

Experimental procedure

Study protocol was performed unilaterally. In case of bilateral CAI, the most unstable ankle was selected for screening and analysis based on medical history. Subjects had to perform a barefooted jump landing in the sagittal (Fig. 2) and frontal plane (Fig. 3) over a hurdle, pushing off on both feet and landing on the tested limb. Jump distance was standardized for the forward jump and side jump to respectively 40% and 33% of subject's height.³⁴ Hurdle height was set at 30cm for the forward jump and 15cm for the side jump. Subjects had to land in the middle of the force plate (AMTI, 250Hz, Watertown, Massachusetts, USA). Subjects were allowed to familiarize themselves with the landing task, as a warming up exercise for both the non-taped and taped condition, starting without hurdle and then gradually building up to the demanded height to avoid fear of movement. After landing, subjects had to place their hands

immediately on their pelvis and had to maintain balance for at least 5". Trials were discarded if subjects did not take off on both feet, did not 'stick' the landing (i.e. if the foot shifted), removed their hands from their pelvis, touched the ground with the contralateral leg, or pushed their legs together to maintain balance. Trials were repeated until in total 5 successful trials were registered for each plane. All subjects first performed the forward jump, followed by the side jump. A rest period of 30" was used between trials, 3' between motion planes, and 10' between conditions. To avoid learning effect and influence of fatigue, subjects were randomized with a block size of 4 to perform the protocol first with or without tape. This was done before the start of the measurements by drawing lots from a bowl containing four papers with 2 of them indicating to start with tape and 2 without tape. After every 4 subjects randomization was in balance. After completion of each landing task, difficulty level and subjective feeling of stability at the ankle joint were documented using a VAS.

To evaluate the effect of the tape on ankle motion during the impact phase of the landing protocol, 3D kinematics were registered with an eight camera opto-electronic setup (Qualisys, Oqus, 250Hz, Sweden) which was positioned around the force plate. Reflective markers were placed on the lower limb (lateral malleolus, medial malleolus, lateral epicondyle, medial epicondyle, and a cluster of 4 on the lateral side of the leg) and on the foot (calcaneus, and first and fifth metatarsal head) to capture ankle motion (Figure 1 and 2).

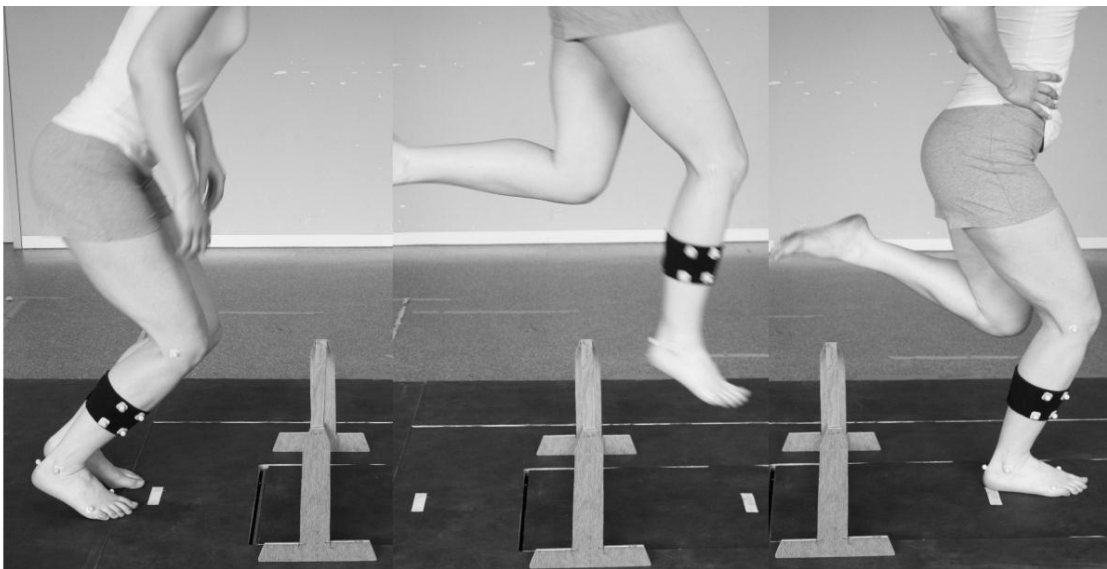


Figure 2. Forward jump protocol

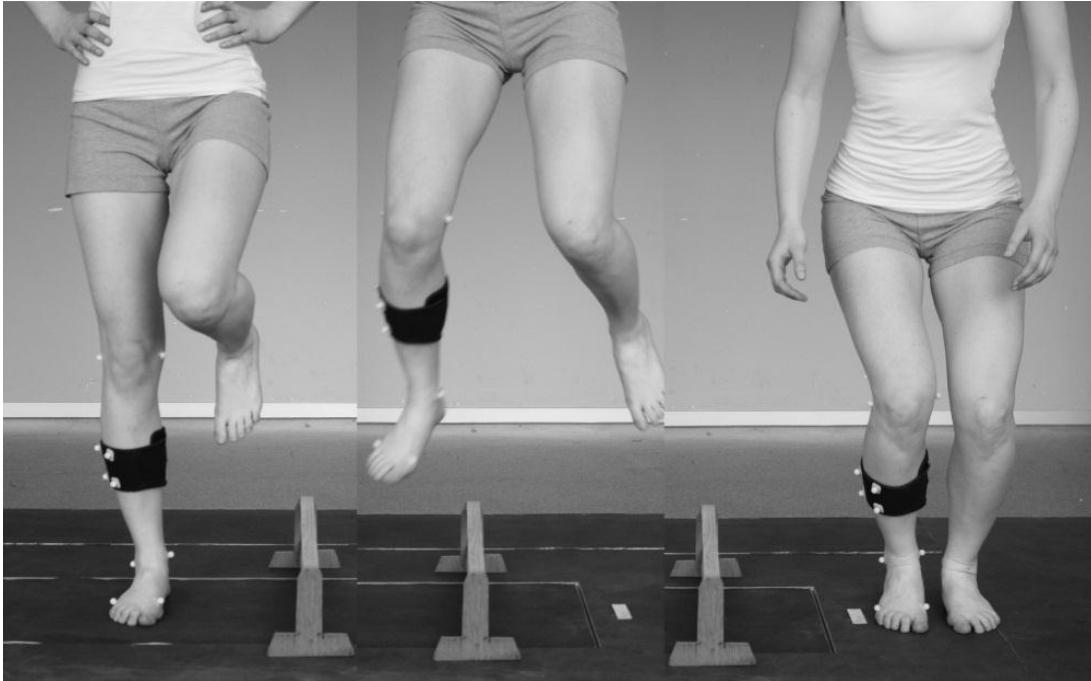


Figure 3. Side jump protocol

Data analysis

Force data were processed using Matlab (The Mathworks Inc., Natick, Massachusetts, US). Data were filtered using a fourth order Butterworth low-pass filter of 15Hz. The modified dynamic postural stability index (DPSI) and its directional stability indices (anterior/posterior (APSI), mediolateral (MLSI) and vertical stability index (VSI)) were calculated for the first 3 seconds after landing.⁴³ Touch down during the landing task was registered using the vertical ground reaction force with a threshold set at 15N. Kinematic data were processed using Visual 3D (C-motion, Germantown, MD). Marker coordinates were filtered using a fourth order Butterworth low-pass filter of 15 Hz. Angular position of the ankle at touch down and ROM in the different planes during the post landing phase (touch down (TD) till 200ms after) were determined to evaluate tape influence on landing kinematics.

Statistical analysis was performed in SPSS 22 (SPSS Inc., Chicago, Illinois 60606, U.S.A.). Study variables were divided into three main constructs, i.e. kinematics, postural stability measures and subjective self-reported measures (VAS scales). Normality of the data was evaluated by means of the Kolmogorov-Smirnov test. An analysis of variance for repeated measures was performed to evaluate the main effect of the tape intervention on these three constructs. When a significant main effect of the intervention was established, paired Student's t-tests were performed on the individual variables to identify specific intervention outcomes. The significant alpha level was set at 0.05.

Results

Three subjects (two female and one male) were excluded because they reported discomfort while performing the jump landing tasks, resulting in 25 subjects with CAI for analysis. There was no significant difference in the amount of trials performed per subject to complete 5 successful trials between the non-taped and taped condition for both the forward jump (resp. 9.9 (3.3) and 9.4 (2.6), $p=0.636$) and the side jump (resp. 8.5 (2.3) and 8.4 (2.7), $p=0.913$).

Tape

3D kinematics showed that the administered tape straps altered foot position at TD and restricted ROM after landing (Table 1). Repeated measures ANOVA indicated a significant main effect of tape on ankle kinematics ($p<0.001$). Paired Student's T-tests displayed that for both the forward jump and side jump, the foot position was significantly less plantar flexed (resp. $p<0.001$, $p=0.001$) and less inverted (resp. $p=0.031$, $p<0.001$) at TD. ROM after TD was significantly restricted in all motion planes for the forward jump, and in the sagittal and transversal plane for the side jump.

Table 1. Mean (SD) ankle angular position at, and ROM after touch down

Forward jump	No tape	Tape	Mean diff [95% CI]	P-value
PF(+)/DF(-) angle at TD (°)	36.1 (5.9)	32.8 (5.7)	3.3 [2.2, 4.4]	<0.001*
INV(+)/EV(-) angle at TD (°)	-6.9 (7.9)	-7.9 (7.8)	1.0 [0.1, 1.9]	0.031*
ADD (+)/ABD(-) angle at TD (°)	2.9 (6.7)	3.2 (6.9)	-0.4 [-1.2, 0.5]	0.422
PF/DF ROM (°)	43.6 (6.0)	40.0 (5.3)	3.6 [2.5, 4.7]	<0.001*
INV/EV ROM (°)	9.5 (2.7)	7.4 (2.5)	2.1 [1.4, 2.8]	<0.001*
ABD/ADD ROM (°)	16.8 (5.1)	15.3 (4.3)	1.5 [0.6, 2.5]	0.004*
Side Jump				
PF(+)/DF(-) angle at TD (°)	32.1 (6.2)	29.4 (5.1)	2.7 [1.3, 4.1]	0.001*
INV(+)/EV(-) angle at TD (°)	-2.5 (8.6)	-5.4 (8.4)	2.9 [1.6, 4.2]	<0.001*
ADD (+)/ABD(-) angle at TD (°)	-3.3 (6.2)	-2.5 (6.8)	-0.7 [-1.9, 0.4]	0.206
PF/DF ROM (°)	45.5 (6.1)	41.9 (5.4)	3.6 [2.5, 4.6]	<0.001*
INV/EV ROM (°)	11.6 (3.0)	10.9 (2.5)	0.6 [-0.3, 1.6]	0.191
ABD/ADD ROM (°)	12.3 (4.3)	11.3 (3.8)	1.0 [0.1, 1.9]	0.038*

(PF=plantar flexion; DF=dorsiflexion; INV=inversion; EV=eversion; ADD=adduction; ABD=abduction; Mean diff=Mean difference; CI=confidence interval; * indicates statistical significance $p<0.05$.)

VAS scores

There was a significant main effect of taping on our subjective outcome measures ($p=0.001$). Paired samples t-tests showed that scores for subjective feelings of instability were significantly lower in the taped condition compared to the non-taped condition for both the forward jump ($p<0.001$) and the side jump ($p=0.016$). Analysis of subjective appraisal of the difficulty level of the performed task, however, showed no significant differences between non-taped and taped condition (Table 2).

Dynamic postural stability index

Repeated measures ANOVA revealed no main effect of tape on the postural stability measures registered during our landing protocol by means of the DPSI and its directional indices ($p=0.921$) (Table 2).

Table 2. Mean (SD) VAS scores and stability indices during landing tasks with and without tape .

Forward jump				
Difficulty level (VAS, cm)	4.59 (2.08)	4.12 (1.91)	0.47 [-0.48, 1.42]	0.315
Instability level (VAS, cm)	4.50 (2.21)	2.66 (2.50)	1.85 [0.94, 2.76]	<0.001*
APSI	0.110 (0.010)	0.109 (0.009)	0.001 [-0.001, 0.003]	NS
MLSI	0.024 (0.006)	0.023 (0.004)	0.001 [-0.001, 0.003]	NS
VSI	0.307 (0.026)	0.311 (0.027)	-0.004 [-0.118, 0.004]	NS
DPSI	0.327 (0.025)	0.331 (0.027)	-0.003 [-0.119, 0.004]	NS
Side Jump				
Difficulty level (VAS, cm)	3.69 (2.44)	3.26 (2.20)	0.43 [-0.42, 1.28]	0.310
Instability level (VAS, cm)	4.27 (2.13)	3.24 (2.19)	1.02 [0.21, 1.84]	0.016*
APSI	0.027 (0.006)	0.026 (0.005)	0.001 [-0.0003, 0.002]	NS
MLSI	0.089 (0.008)	0.088 (0.007)	0.0001 [-0.002, 0.003]	NS
VSI	0.273 (0.027)	0.270 (0.022)	0.003 [-0.004, 0.009]	NS
DPSI	0.289 (0.027)	0.286 (0.022)	0.003 [-0.004, 0.010]	NS

Mean diff=Mean difference; CI=confidence interval; * indicates statistical significance $p<0.05$. NS indicates that the main effect of tape on study variables was not significant, no further analysis was performed.

Discussion

Our study evaluated the effect of a non-elastic tape protocol on the dynamic postural control during a sagittal and frontal plane jump landing protocol. The taping procedure used in this study was effective in altering foot position at touch down and restricting ROM after landing. Kinetic results indicated, however, no significant differences between the non-taped and taped condition on the dynamic postural control measured by means of the DPSI and its directional indices. Subjective VAS scores did reveal that subjects felt less unstable at the ankle joint in the taped condition for both jump landing protocols. However, the tape had no influence on the perceived difficulty level of the performed functional tasks.

From a clinical perspective, these postural control results are unexpected in view of the preventative effect tape has on ankle sprain incidence.²¹ However, these results are in agreement with other studies which found no effect of a brace as an external support on postural stability in subjects with CAI during dynamic landing.^{9, 40} Gribble et al. and Wikstrom et al. did not find any significant influence of a brace on postural control by means of time-to-stabilization⁹ and the DPSI.⁴⁰ Furthermore, the results are in agreement with previous studies investigating the effect of tape on postural control during less dynamic tasks in subjects with CAI. Hopper et al. evaluated the effect of Mulligan ankle taping during static balance and during unilateral stance while performing dynamic computerized tracking balance tasks. They found no significant effect of the tape on their balance parameters. In addition, Delahunt et al., Sawkins et al., and Wheeler et al. used the Star Excursion Balance Test to evaluate the capacity of tape (subtalar sling and fibular reposition tape⁵, a combination of anchors, stirrups, figure of six and a heel lock³³, and fibular reposition tape³⁹) on dynamic postural control, but failed to demonstrate a positive effect. Gribble et al. argued that a possible explanation for the lack of improvement in their brace study may be found in the fact that the measuring technique based on 'time to stabilization' may not be sensitive enough to detect improvement.⁹ This might also be argued for the results in our study using DPSI.

Another possible explanation for the lack of effect of external support on postural control may be the underlying selected control strategy used to maintain one's postural stability during static or dynamic conditions. When maintaining balance by performing inversion and eversion motion at the ankle joint to control perturbations, it is referred to as an 'ankle strategy'. Subjects with CAI, however, have been demonstrated to use a more proximal 'hip strategy', which is assumed to be less efficient to control balance possibly resulting in higher shear forces with the ground.²⁵ Therefore, when applying an external support at the ankle, hence restricting motion at the ankle joint, subjects with CAI might be

even more compelled to use this 'hip strategy'. Taping may have a different impact on balance recovery in subjects prioritizing the 'hip strategy' over the 'ankle strategy'. Teasing out such subtle differences would require advanced whole body motion analysis techniques beyond the scope of this study, such as for example applying induced acceleration analysis during the initial impact phase.¹⁰

If taping and bracing do not have a positive influence on postural stability, there must be some other explanation for the lower incidence rates for reoccurrence of acute lateral ankle sprains^{21, 24}. As mentioned before, a recent meta-analysis by Raymond et al. debunked the effect of taping on proprioception in subjects with CAI based on 4 included articles.^{17, 18, 28, 29} Literature on the effect of taping on neuromuscular control in subjects with CAI is even more scarce. Karlsson and Anderson (1992) demonstrated a significant decreased reaction time of the peroneus longus after application of the Gibney Basketweave taping technique during simulated ankle sprains in unstable ankles, without reaching the level of healthy ankles.¹⁹ Furthermore, tape is believed to restrict mechanical laxity in subjects with CAI.^{16, 22} Miller et al. demonstrated even better inversion and eversion rotation restriction after an exercise protocol when using a tape compared to a brace.²² Although it is indicated that tape loses some of its restriction capacity during and after physical activity, it still decreases range of motion compared to a non-taped condition.^{7, 26} Next to controlling ROM, tape is also believed to have its effect by controlling foot position at the moment of touch down.⁶ The tape applied in our study resulted in a less plantar flexed and less inverted position at touch down and also a restriction of the ROM. This altered ankle configuration could result in reduced injury rates, as they restrict the motions linked to ankle sprain events. A model driven study suggested that increased plantar flexion at touchdown might be the primary mechanism to have an increased susceptibility for ankle sprains⁴⁴ Most likely, a combination of these factors described above might partly explain the reduction in injury rate.

VAS scores indicated that the taped condition did decrease the feeling of instability as hypothesized, even though only a few strips of tape were used. These results coincide with previous studies on the effect of tape in subjects with CAI.^{5, 33} It is argued that this is an important treatment effect, possibly even placebo, which should not be underestimated because the perception of a patient or athlete may very well influence the effectiveness of the treatment modality in preventing injury.³³ Perceived difficulty level of the landing tasks, however was not influenced by our taping procedure. This was also objectively expressed in the equal amount of trials needed for 5 successful performances between the non-taped and taped condition.

Other taping procedures are of course possible as described in the studies mentioned above. Especially when engaging a sporting activity, a combination of several techniques to guarantee the

firmness of the tape for a longer time period is advisable. The tape used in the current study consisted only of a few strips. We only looked at the immediate effect of tape and found our taping procedure effective in altering foot position at landing and limiting ROM. Therefore, the taping procedure was assessed as suitable to evaluate its effect on our outcome parameter, without excluding other possible working mechanisms of tape as discussed above. A possible limitation is that the current study was performed barefooted which has its impact on landing kinetics.³⁵ Furthermore, a considerable total amount of trials were performed possibly inducing fatigue. By randomizing the sequence in performing the landing tasks with or without tape, this effect was somewhat overcome to be able to evaluate the effect of our intervention. Finally, the evaluation of joint kinematics in this study was performed to assess if the taping procedure had a mechanical impact which in his turn could affect postural control measures. The actual effect of tape on the ankle joint kinematics itself was not fully explored as it was out of the scope of the current study.

Conclusion

Results of the present study indicate that the taping procedure, altering landing kinematics, does not improve postural control in a frontal and sagittal plane dynamic landing task in subjects with CAI. Perceived instability, however, did improve which is also an important treatment outcome parameter as it may very well influence the effectiveness of the treatment modality in preventing injury. Therefore, taping should be considered as a treatment modality by clinicians. The use of postural control, solely based on ground reaction forces, as a parameter to evaluate the effect of external support should be reconsidered based on the known control strategies used to maintain balance in subjects with CAI.

References

- (1) Arnold BL, De La Motte S, Linens S, Ross SE. Ankle instability is associated with balance impairments: a meta-analysis. *Med Sci Sports Exerc* 2009;41(5):1048-1062.
- (2) Brown CN, Bowser B, Orellana A. Dynamic postural stability in females with chronic ankle instability. *Med Sci Sports Exerc* 2010;42(12):2258-2263.
- (3) Brown CN, Mynark R. Balance deficits in recreational athletes with chronic ankle instability. *J Athl Train* 2007;42(3):367-373.
- (4) Callaghan MJ. Role of ankle taping and bracing in the athlete. *Br J Sports Med* 1997;31(2):102-108.
- (5) Delahunt E, McGrath A, Doran N, Coughlan GF. Effect of taping on actual and perceived dynamic postural stability in persons with chronic ankle instability. *Arch Phys Med Rehabil* 2010;91(9):1383-1389.
- (6) Delahunt E, O'Driscoll J, Moran K. Effects of taping and exercise on ankle joint movement in subjects with chronic ankle instability: a preliminary investigation. *Arch Phys Med Rehabil* 2009;90(8):1418-1422.
- (7) Fleet K, Galen S, Moore C. Duration of strength retention of ankle taping during activities of daily living. *Injury* 2009;40(3):333-336.
- (8) Goldie PA, Bach TM, Evans OM. Force platform measures for evaluating postural control: reliability and validity. *Arch Phys Med Rehabil* 1989;70(7):510-517.
- (9) Gribble PA, Taylor BL, Shinohara J. Bracing does not improve dynamic stability in chronic ankle instability subjects. *Phys Ther Sport* 2010;11(1):3-7.
- (10) Hamner SR, Delp SL. Muscle contributions to fore-aft and vertical body mass center accelerations over a range of running speeds. *J Biomech* 2013;46(4):780-787.
- (11) Han K, Ricard MD. Effects of 4 weeks of elastic-resistance training on ankle-evertor strength and latency. *J Sport Rehabil* 2011;20(2):157-173.
- (12) Harriss DJ, Atkinson G. Ethical standards in sport and exercise science research: 2014 update. *Int J Sports Med* 2013;34(12):1025-1028.
- (13) Hertel J. Functional Anatomy, Pathomechanics, and Pathophysiology of Lateral Ankle Instability. *J Athl Train* 2002;37(4):364-375.
- (14) Hertel J. Sensorimotor deficits with ankle sprains and chronic ankle instability. *Clin Sports Med* 2008;27(3):353-70, vii.
- (15) Hopper D, Samsson K, Hulenik T, Ng C, Hall T, Robinson K. The influence of Mulligan ankle taping during balance performance in subjects with unilateral chronic ankle instability. *Phys Ther Sport* 2009;10(4):125-130.
- (16) Hubbard TJ, Cordova M. Effect of ankle taping on mechanical laxity in chronic ankle instability. *Foot Ankle Int* 2010;31(6):499-504.
- (17) Hubbard TJ, Kaminski TW. Kinesthesia Is Not Affected by Functional Ankle Instability Status. *J Athl Train* 2002;37(4):481-486.
- (18) Jerosch J, Hoffstetter I, Bork H, Bischof M. The influence of orthoses on the proprioception of the ankle joint. *Knee Surg Sports Traumatol Arthrosc* 1995;3(1):39-46.

- (19) Karlsson J, Andreasson GO. The effect of external ankle support in chronic lateral ankle joint instability. An electromyographic study. *Am J Sports Med* 1992;20(3):257-261.
- (20) Liu K, Heise GD. The effect of jump-landing directions on dynamic stability. *J Appl Biomech* 2013;29(5):634-638.
- (21) Mickel TJ, Bottoni CR, Tsuji G, Chang K, Baum L, Tokushige KA. Prophylactic bracing versus taping for the prevention of ankle sprains in high school athletes: a prospective, randomized trial. *J Foot Ankle Surg* 2006;45(6):360-365.
- (22) Miller H, Needle AR, Swanik CB, Gustavsen GA, Kaminski TW. Role of external prophylactic support in restricting accessory ankle motion after exercise. *Foot Ankle Int* 2012;33(10):862-869.
- (23) O'Driscoll J, Delahunt E. Neuromuscular training to enhance sensorimotor and functional deficits in subjects with chronic ankle instability: A systematic review and best evidence synthesis. *Sports Med Arthrosc Rehabil Ther Technol* 2011;3:19.
- (24) Olmsted LC, Vela LI, Denegar CR, Hertel J. Prophylactic Ankle Taping and Bracing: A Numbers-Needed-to-Treat and Cost-Benefit Analysis. *J Athl Train* 2004;39(1):95-100.
- (25) Pintsaar A, Brynhildsen J, Tropp H. Postural corrections after standardised perturbations of single limb stance: effect of training and orthotic devices in patients with ankle instability. *Br J Sports Med* 1996;30(2):151-155.
- (26) Purcell SB, Schuckman BE, Docherty CL, Schrader J, Poppy W. Differences in ankle range of motion before and after exercise in 2 tape conditions. *Am J Sports Med* 2009;37(2):383-389.
- (27) Raymond J, Nicholson LL, Hiller CE, Refshauge KM. The effect of ankle taping or bracing on proprioception in functional ankle instability: a systematic review and meta-analysis. *J Sci Med Sport* 2012;15(5):386-392.
- (28) Refshauge KM, Kilbreath SL, Raymond J. The effect of recurrent ankle inversion sprain and taping on proprioception at the ankle. *Med Sci Sports Exerc* 2000;32(1):10-15.
- (29) Refshauge KM, Raymond J, Kilbreath SL, Pengel L, Heijnen I. The effect of ankle taping on detection of inversion-eversion movements in participants with recurrent ankle sprain. *Am J Sports Med* 2009;37(2):371-375.
- (30) Riemann BL. Is There a Link Between Chronic Ankle Instability and Postural Instability? *J Athl Train* 2002;37(4):386-393.
- (31) Ross SE, Guskiewicz KM. Examination of static and dynamic postural stability in individuals with functionally stable and unstable ankles. *Clin J Sport Med* 2004;14(6):332-338.
- (32) Ross SE, Guskiewicz KM, Yu B. Single-leg jump-landing stabilization times in subjects with functionally unstable ankles. *J Athl Train* 2005;40(4):298-304.
- (33) Sawkins K, Refshauge K, Kilbreath S, Raymond J. The placebo effect of ankle taping in ankle instability. *Med Sci Sports Exerc* 2007;39(5):781-787.
- (34) Sell TC. An examination, correlation, and comparison of static and dynamic measures of postural stability in healthy, physically active adults. *Phys Ther Sport* 2012;13(2):80-86.
- (35) Shultz SJ, Schmitz RJ, Tritsch AJ, Montgomery MM. Methodological considerations of task and shoe wear on joint energetics during landing. *J Electromyogr Kinesiol* 2012;22(1):124-130.
- (36) Tanen L, Docherty CL, Van Der Pol B, Simon J, Schrader J. Prevalence of Chronic Ankle Instability in High School and Division I Athletes. *Foot Ankle Spec* 2013.

- (37) Verhagen E, van der Beek A, Twisk J, Bouter L, Bahr R, van Mechelen W. The effect of a proprioceptive balance board training program for the prevention of ankle sprains: a prospective controlled trial. *Am J Sports Med* 2004;32(6):1385-1393.
- (38) Verhagen EA, van der Beek AJ, van Mechelen W. The effect of tape, braces and shoes on ankle range of motion. *Sports Med* 2001;31(9):667-677.
- (39) Wheeler TJ, Basnett CR, Hanish MJ et al. Fibular taping does not influence ankle dorsiflexion range of motion or balance measures in individuals with chronic ankle instability. *J Sci Med Sport* 2013.
- (40) Wikstrom EA, Arrigenna MA, Tillman MD, Borsa PA. Dynamic postural stability in subjects with braced, functionally unstable ankles. *J Athl Train* 2006;41(3):245-250.
- (41) Wikstrom EA, Tillman MD, Borsa PA. Detection of dynamic stability deficits in subjects with functional ankle instability. *Med Sci Sports Exerc* 2005;37(2):169-175.
- (42) Wikstrom EA, Tillman MD, Chmielewski TL, Cauraugh JH, Borsa PA. Dynamic postural stability deficits in subjects with self-reported ankle instability. *Med Sci Sports Exerc* 2007;39(3):397-402.
- (43) Wikstrom EA, Tillman MD, Chmielewski TL, Cauraugh JH, Naugle KE, Borsa PA. Dynamic postural control but not mechanical stability differs among those with and without chronic ankle instability. *Scand J Med Sci Sports* 2010;20(1):e137-e144.
- (44) Wright IC, Neptune RR, van den Bogert AJ, Nigg BM. The influence of foot positioning on ankle sprains. *J Biomech* 2000;33(5):513-519.

Foot orientation affects muscle activation levels of ankle stabilizers in a single-legged balance board protocol

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Abstract

Objective: The main goal of balance training is regaining a normal neuromuscular control to a functional level. Although uniaxial balance boards are commonly used, no research has been done on the effect of foot orientation on muscle activation levels. Therefore, the objective of this study was to investigate the effect of foot orientation on muscle activation levels and modulation of the ankle stabilizing muscles in a single-legged balance protocol on a uniaxial balance board.

Methods: Sixty-nine healthy subjects (age:21.8±1.7y; mass:67.5±11.9kg; body height:174.7±8.6 cm; BMI:21.5±3.0) participated in this study. Subjects were asked to keep their balance during a single leg stance on a uniaxial balance board for four different foot orientations, aligning the board's rotation axis with frontal, sagittal, diagonal and subtalar axes of the foot, respectively. Surface electromyography registered muscle activity of peroneus longus, tibialis anterior, medial and lateral gastrocnemius muscles.

Results: Highest muscle activation levels and modulation for the peroneus longus were registered exercising along the frontal axis; for the tibialis anterior along the diagonal axis; for the medial gastrocnemius along the sagittal axis; and for the lateral gastrocnemius along the diagonal axis.

Conclusion: Foot orientation modifications on a uniaxial balance board allows to differentially target specific ankle stabilizing muscles during balance training.

Introduction

Balance protocols are often part of the rehabilitation process of lower leg musculoskeletal injuries. Balance is defined as the capacity of a person to preserve their center of mass within their base of support. The capacity to do this depends on the efficient integration of afferent visual, vestibular and somatosensory inputs to generate an adequate efferent neuromuscular response.³⁸ Musculoskeletal lower leg injuries such as an ankle sprain are believed to affect balance capabilities.²² As a result of an ankle sprain, damage to the mechanoreceptors in the ankle joint has been suggested to lead to partial deafferentation.^{8, 15} Khin-Myo-Hla et al. state that this deafferentation may suppress gamma motorneuron activity and cause alterations in the muscle spindle sensitivity.¹² These deficits might lead to impaired balance, an increased risk to resprain, or evolve to chronic functional instability of the ankle joint.^{10, 37} Therefore, specific ankle rehabilitation programs involving balance training are common approaches to minimize consequences of ankle injuries and prevent recurrence.

The main goal of balance training is regaining a normal neuromuscular control around the ankle to a functional level, by maximally stimulating the muscle activity levels of the ankle stabilizing muscles. Various studies have shown improvements of postural control through balance training programs.^{8, 11, 17, 20, 31} Not only the curative effect of balance training has been demonstrated, but also the preventative effect on overall lower limb injuries and more specifically ankle sprains.^{24, 31} Consequently, the risk of an ankle sprain is significantly reduced in populations who subsequently undergo balance training.^{11, 31} As explanation, it is suggested that long-term balance training results in a higher stimulation of muscle spindles.³ This higher stimulation would improve neuromuscular control and, therefore, contribute to the functional stability of the ankle joint. However, balance protocols differ in duration, frequency, used device, and progression of the exercises.¹⁸ At this moment, it is not known which exercises best serve the rehabilitation goals.

It has been suggested that higher muscle activity levels during the balance protocol are expected to speed up the rehabilitation process and a quicker return to preinjury functional levels.⁷ The magnitude of muscle activity depends on the stability of the used device.³⁴ For different multidirectionally unstable devices such as a trampoline, wobble board, swiss ball, dyna disc or BOSU balance trainer, muscle activity levels of ankle stabilizing muscles have been assessed and compared.^{14, 34, 36} These devices have in common that there is no control over the rotation direction in which the ankle is challenged. Uniaxial balance boards, on the other hand, allow for

uniaxial rotational instability which depends on foot orientation on the board. Whilst uniaxial balance boards are commonly used devices for balance training in the clinical practice, to the authors' knowledge no research has been done yet that identified the effect of foot orientation on muscle activation levels of different ankle stabilizing muscles. This may be useful when rehabilitation is meant to target resolving defects of specific ankle stabilizing muscles. Especially in the early stages of rehabilitation, this focus on a specific muscle might be desirable before using a general multiaxial device. The different foot orientations used in the clinical practice are based on the movement they create around the ankle joint. It is believed that depending on foot orientation, muscle activation levels and amount of modulation of the different ankle stabilizing muscles will vary according to their anatomical functions, however scientific research is lacking. The most commonly used foot orientation is with the axis of the device aligned with a frontal foot axis, creating a inversion-eversion instability which can be considered the most common mechanism of ankle sprains. It remains, however, unclear how muscle activation and modulation of the different ankle stabilizing muscles differ when working at other foot orientations.

The purpose of this study was primarily to determine muscle activation levels of four ankle muscles, contributing to dynamic stability of the ankle joint, during a single-leg balance board protocol. The muscle activation levels of each specific muscle will be compared for four different foot orientations. We hypothesized that individual ankle muscles would be maximally activated for the foot orientation in which they are maximally challenged with respect to their primary anatomical function. Therefore, the hypothesis was that for the peroneus longus alignment with the subtalar axis would provoke highest muscle activations, for the tibialis anterior a diagonal axis, and for the medial and lateral gastrocnemius a sagittal axis. In addition, modulation in muscle activity as an estimate of responsiveness to balance board motions, was compared between the different axes for each muscle.

Methods

Subjects

A group of 69 healthy subjects (age: $21.8 \pm \text{SD } 1.7$; mass: $67.5 \pm 11.9\text{kg}$; body height: $174.7\text{cm} \pm \text{SD } 8.6$; BMI: 21.48 ± 2.99) was tested. The population consisted of 38 female and 31 male participants between 18 and 25 years old. Participants were excluded from the study if they had a

musculoskeletal injury to the lower limb, limiting normal activity, in the last year; if they suffered from self-reported ankle instability (repetitive sprains, periods of giving way); a systemic disease which could influence balance performance; or if they were pregnant at the moment of testing. Anthropometric data was collected, and the participants completed a questionnaire to establish their medical history. The Ghent University Hospital ethics committee approved this study and all subjects signed the informed consent before participation.

Procedures

During the experiment, participants were asked to keep their balance on a uniaxial balance board, while their muscle activity was registered. They were instructed to perform a single-leg stance on the balance board with the knee of the stance leg slightly flexed (knee perpendicular above the toes). Compensating movements with the arms and the contralateral free leg to keep balance were permitted. Every participant was tested unilaterally, and the stance leg was chosen through randomization (33 right and 36 left legs tested). Four different foot orientations were tested (fig. 1). For every subject, the sequence of the foot orientations was randomized as a set by drawing lots. This “set”, containing the orientation order, was then repeated for this subject 3 times. In each set, every foot orientation was performed during 15 seconds with a 30-second rest interval. Rest interval between sets was two minutes. Before each measurement, the participants supported themselves with their hands on a chair for balance. When ready, they released the chair and the measurement was started. Whenever the balance board or contralateral foot touched the ground or the participants searched support with their hands, they had to restore as quickly as possible their balance and continue the exercise.

The uniaxial balance board (custom made) used in this study had a length of 50 cm and a width of 38 cm. Two half spheres are fixated onto the base, creating uniaxial instability. The half sphere had a height of 4 cm and a diameter of 7.5 cm. Foot positions were marked on the balance board, as shown in figure 1. When the rotational axis underneath the balance board is aligned parallel with the frontal axis of the foot (F-axis), instability occurs in the frontal plane (inversion/eversion). Alignment with the sagittal axis (S-axis) is perpendicular to the frontal axis, leading to instability in the sagittal plane (plantar flexion/dorsiflexion). The third foot orientation has an alignment with a diagonal foot axis (D-axis), 45° externally rotated from the F-axis and creating a plantarflexion/eversion and dorsiflexion/inversion motion. The last foot orientation has an alignment with an axis that is 16° internally rotated from the frontal axis, matching the

anatomical orientation of the subtalar joint axis (ST-axis) and leading to inversion/eversion instability along the subtalar axis.

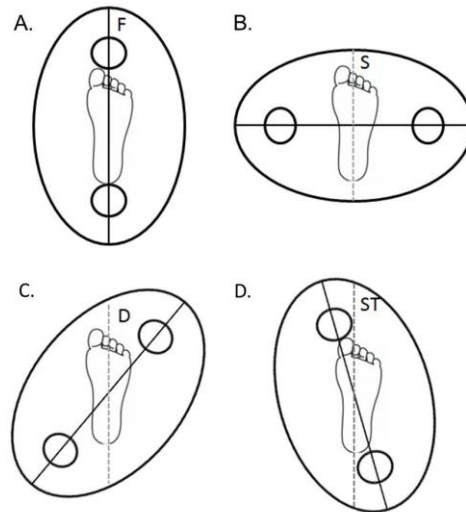


Figure 1. Different foot positions in relation to axis created by two spheres underneath the balance board: along A. F=Frontal axis, B. S=Sagittal axis, C. D= Diagonal axis, and D. ST=Subtalar joint axis

EMG signal acquisition and processing

Muscle activity of the m. tibialis anterior (TA), m. peroneus longus (PL), medial (MG) and lateral (LG) m. gastrocnemius was registered using surface electromyography at 1000Hz (Myosystem 1400A, Noraxon U.S.A. Inc, Scottsdale, Arizona 85254, U.S.A.). To reduce impedance, the skin surface was shaved and cleaned with ether to remove dead skin and grease. Disposable bipolar Ag/AgCl surface electrodes with conducting gel and 2cm diameter were placed with an inter-electrode distance of 2 cm center-to-center and parallel to the muscle fibers according to SENIAM guidelines (www.seniam.org). The wires and electrodes were fixated with gauze to minimize the effect of motion artifacts.

For the processing of the EMG data, the MyoResearch XP Master Edition (Noraxon U.S.A. Inc, Scottsdale, Arizona 85254, U.S.A.) was used. The raw data of these EMG signals were full-wave rectified and smoothed using a moving average window of 100 ms. Only the intervals where the participant was effectively balancing, as defined below, on the balance board were taken into account. To be able to omit the periods in which the participant was not balancing, a synchronized mark was placed using a hand-held external trigger whenever the subject lost balance. This was based on real time visual detection of the rim of the balance board touching the ground, or any

attempt by the participant to find support with the contralateral leg on the floor or with the hands on the chair. Another mark was placed as soon as unsupported balancing was restored. Subsequently, the time periods when the participant was balancing unsupported were assembled and the Root Mean Square (RMS), which represents the mean of the varying muscle activity magnitude, was calculated to represent overall activation levels throughout the trial. The goal of this study was to evaluate within one muscle which foot orientation generated highest muscle activity levels for that muscle. To emphasize this and avoid interpretations based on absolute RMS values, all RMS values were normalized ⁴ to the RMS value of the foot orientation along the F-axis which is considered the most commonly used foot orientation in clinical practice.

In addition, variation in muscle amplitude was calculated to quantify muscle modulation during the balance task. Therefore, the rectified and smoothed EMG signal was exported from MyoResearch and further processed in Excel. To reflect the variation in muscle amplitude, the signal was differentiated representing the time dependent changes. Subsequently, the mean magnitude of these changes was calculated as an estimate for modulation of muscle contractions. By differentiating the smoothed EMG signal, it is estimated that modulation represents neuromuscular responsiveness to balance board motions. Modulation is largely independent from muscle activation levels, considering that high activation levels may be constant (e.g. during increased co-contractions) or varying (e.g. responding to balance board motions).

Statistical analysis

Statistical analysis was performed in SPSS 20 (SPSS Inc., Chicago, Illinois 60606, U.S.A.). Differences in muscle activity according to axis orientation, and differences in muscle modulation, were evaluated using repeated measures ANOVA. Post hoc multiple pairwise comparisons with a Bonferroni correction were performed to identify specific differences. Significance level was set at $p \leq 0.05$.

Results

The ANOVA showed significant differences in muscle activation and modulation according to the foot orientation for all muscles tested ($p < 0.001$). The post hoc comparison results are presented in table 1 for muscle activation levels, and in table 2 for modulation in muscle activity. Overall, the

same results were found for muscle activation magnitude and modulation. Partial eta square (η_p^2), indicating the effect size for the repeated measure ANOVA respectively for muscle activation level and modulation, was 0.607 and 0.517 for the PL, 0.318 and 0.393 for the TA, 0.499 and 0.445 for the MG, and 0.465 and 0.349 for the LG. The total durations of the assembled time periods for analysis were for the F-axis $26.12 \pm 5.74s$ (range 12.60s - 42.70s), for the S-axis $25.04 \pm 5.13s$ (range 16.69s, - 41.79s), for the D-axis $25.33 \pm 5.31s$ (range 12.90s - 38.69s), and for the ST-axis $26.58 \pm 5.51s$ (range 12.29 s - 41.80s). A general linear model with repeated measures showed no main effect of foot orientation on the time included for analysis ($p=0.236$).

Peroneus longus

The peroneus longus showed significantly higher muscle activation levels when the exercise was performed along the F-axis compared to the ST-, D- and the S-axis (Fig. 2). The same results were found for the level of modulation, except for the comparison between the F-axis and the D-axis which did not reach statistical significance ($p=0.060$). With the foot along the S-axis, muscle activation levels and modulation were also significantly lower than with the foot along the D- and ST-axis, whilst there was no significant difference between the latter two.

Tibialis Anterior

Muscle activation levels and modulation of the tibialis anterior muscle were significantly higher when exercising along the D-axis in comparison to along the F-, S- and ST-axis (Figure 3). No significant difference was noted between exercising along the F-, S- and ST-axis.

Medial gastrocnemius

Figure 4 shows significantly higher muscle activation levels in the medial gastrocnemius when exercising along the S-axis in comparison to the ST-, F- and D-axis. Exercising along the F-axis generated significantly lower muscle activation levels compared to all other axes. Foot orientation along the D-axis was not significantly different from ST-axis. The results for modulation were exactly the same.

Lateral gastrocnemius

Figure 5 shows that the lateral gastrocnemius was significantly more activated with the foot positioned along the D-axis compared to all other axes. The foot orientated along the ST-axis

evoked lower activation levels compared to the F-axis. There was no significant difference in muscle activation levels between both the F- and ST-axis compared to the S-axis. Also for the LG, modulation results were the same as for muscle activation levels except for the level of modulation between the F- and ST-axis which was not significantly different.

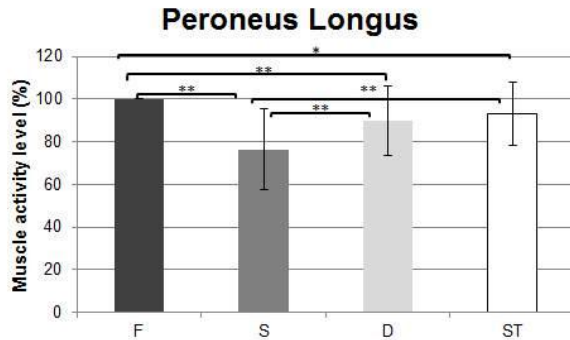


Figure 2. Muscle activity level (%), normalized to the F-axis, of the peroneus longus according to the different axes (F=frontal axis, S=sagittal axis, D=diagonal axis, ST=subtalar axis)(*p<0.05, **p<0.001)

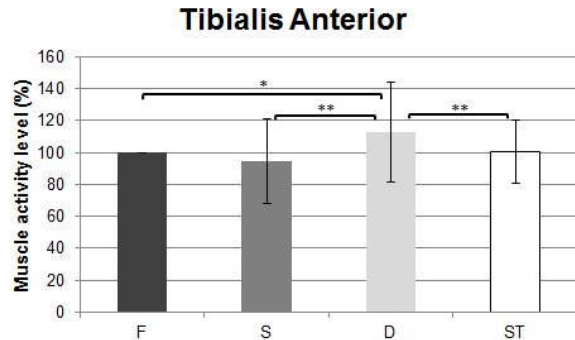


Figure 3. Muscle activity level (%), normalized to the F-axis, of the tibialis anterior according to the different axes (F=frontal axis, S=sagittal axis, D=diagonal axis, ST=subtalar axis)(*p<0.05, **p<0.001)

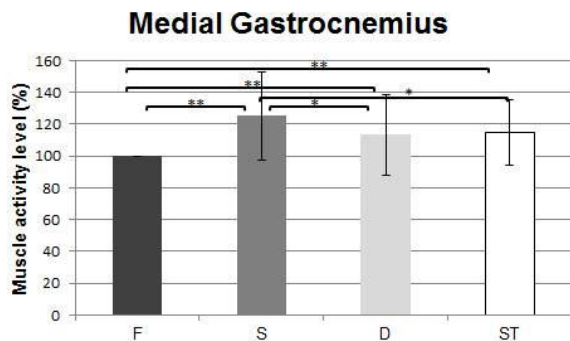


Figure 4. Muscle activity level (%), normalized to the F-axis, of the medial gastrocnemius according to the different axes (F=frontal axis, S=sagittal axis, D=diagonal axis, ST=subtalar axis)(*p<0.05, **p<0.001)

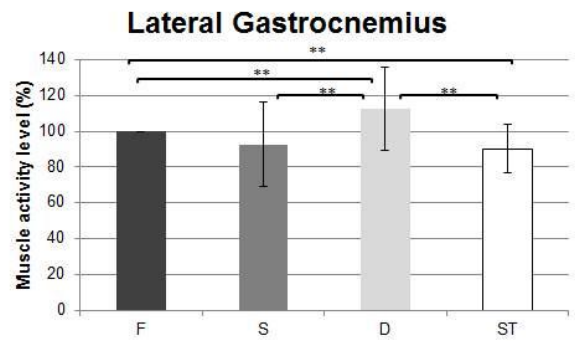


Figure 5. Muscle activity level (%), normalized to the F-axis, of the lateral gastrocnemius according to the different axes (F=frontal axis, S=sagittal axis, D=diagonal axis, ST=subtalar axis)(*p<0.05, **p<0.001)

	Medial gastrocnemius			Lateral gastrocnemius			Peroneus longus			Tibialis anterior		
Axis 1 vs Axis 2	Mean axis 1 (SD)	Mean axis 2 (SD)	P-value	Mean axis 1 (SD)	Mean axis 2 (SD)	P-value	Mean axis 1 (SD)	Mean axis 2 (SD)	P-value	Mean axis 1 (SD)	Mean axis 2 (SD)	P-value
F-S	100	125.2 (27.9)	<0.001*	100	92.6 (23.8)	0.073	100	76.4 (19.2)	<0.001*	100	94.5 (26.4)	0.536
F-ST	100	114.8 (20.9)	<0.001*	100	90.2 (13.7)	<0.001*	100	93.1 (15.1)	0.002*	100	100.7 (20.0)	1.000
F-D	100	113.1 (25.5)	<0.001*	100	112.5 (23.6)	<0.001*	100	89.8 (16.3)	<0.001*	100	112.9 (31.4)	0.007
S-ST	125.2 (27.9)	114.8 (20.9)	0.017*	92.6 (23.8)	90.2 (13.7)	1.000	76.4 (19.2)	93.1 (15.1)	<0.001*	94.5 (26.4)	100.7 (20.0)	0.221
S-D	125.2 (27.9)	113.1 (25.5)	0.005*	92.6 (23.8)	112.5 (23.6)	<0.001*	76.4 (19.2)	89.8 (16.3)	<0.001*	94.5 (26.4)	112.9 (31.4)	<0.001*
ST-D	114.8 (20.9)	113.1 (25.5)	1.000	90.2 (13.7)	112.5 (23.6)	<0.001*	93.1 (15.1)	89.8 (16.3)	0.892	100.7 (20.0)	112.9 (31.4)	<0.001*

Table 1. Results of the post hoc multiple pairwise comparisons, with a Bonferroni correction, of the muscle activity levels (% normalized to F-axis) according to the different axes within 1 muscle (F=frontal axis, S=sagittal axis, ST=subtalar axis, D=diagonal axis, SD=standard deviation)

	Medial gastrocnemius			Lateral gastrocnemius			Peroneus longus			Tibialis anterior		
Axis 1 vs Axis 2	Mean axis 1 (SD)	Mean axis 2 (SD)	P-value	Mean axis 1 (SD)	Mean axis 2 (SD)	P-value	Mean axis 1 (SD)	Mean axis 2 (SD)	P-value	Mean axis 1 (SD)	Mean axis 2 (SD)	P-value
F-S	100	136.1 (35.1)	<0.001*	100	102.5 (34.8)	1.000	100	76.5 (32.5)	<0.001*	100	103.8 (41.5)	1.000
F-ST	100	120.5 (26.9)	<0.001*	100	95.5 (32.1)	0.996	100	92.8 (20.5)	0.034*	100	100.9 (28.9)	1.000
F-D	100	115.4 (27.5)	<0.001*	100	121.4 (38.8)	<0.001*	100	91.3 (26.9)	0.060	100	121.9 (45.6)	0.001*
S-ST	136.1 (35.1)	120.5 (26.9)	0.002*	102.5 (34.8)	95.5 (32.1)	0.281	76.54 (32.5)	92.83 (20.5)	<0.001*	103.8 (41.5)	100.9 (28.9)	1.000
S-D	136.1 (35.1)	115.4 (27.5)	<0.001*	102.5 (34.8)	121.4 (38.8)	<0.001*	76.54 (32.5)	91.3 (26.9)	<0.001*	103.8 (41.5)	121.9 (45.6)	0.001*
ST-D	120.5 (26.9)	115.4 (27.5)	1.000	95.5 (32.1)	121.4 (38.8)	<0.001*	92.83 (20.5)	91.3 (26.9)	1.000	100.9 (28.9)	121.9 (45.6)	<0.001*

Table 2. Results of the post hoc multiple pairwise comparisons, with a Bonferroni correction, of the modulation in muscle activity levels (% \cdot s $^{-1}$) according to the different axes within 1 muscle (F=frontal axis, S=sagittal axis, ST=subtalar axis, D=diagonal axis, SD=standard deviation)

Discussion

This study was the first to evaluate muscle activity levels and modulation of muscle activity according to different foot orientations during single-leg balancing on a uniaxial balance board. Although not all postulated hypothesis were confirmed, there was a specific foot orientation on the balance board for each ankle stabilizing muscle which generated higher muscle activation levels compared to the other orientations. These results matched to a large extent with the primary anatomical function of that muscle. However, some findings may have implications for training protocols. Furthermore, differences in amount of modulation in muscle activity according to the different axes were in general similar to the muscle activity results. Foot orientations evoking highest muscle activity levels, also evoked more modulation in muscle activity.

The four foot orientations defined different movements in the ankle joint in relation to the axis of the balance board. These orientations evoked different muscle activation levels in the individual ankle stabilizing muscles. The PL was assumed to be most active along the ST-axis because of the more anatomical approximation of the inversion/eversion motion in the subtalar joint and the eversion function of the PL.¹⁹ The subtalar joint is oriented from posterolateral to anteromedial in an angle of approximately 16° in relation to the frontal axis.²⁶ Orientation along this subtalar axis did indeed evoke more activity in the PL than along the S- and D-axis. The S-axis evoked lowest muscle activity levels, which could be expected due to the absence of a inversion/eversion motion. Between the two inversion/eversion axes (ST- and F-axis), however, the amount of muscle activity of the PL evoked along the F-axis was higher in spite of its anatomical function being more explicit along the ST-axis. This was not expected and therefore the postulated hypothesis has to be rejected. For the TA, highest muscle activity levels were evoked when exercising along the D-axis, as was expected. The TA has a dorsiflexion/inversion function which correlates with the plantar flexion/eversion and a dorsiflexion/inversion motion caused along the D-axis.¹⁹ Remarkably, the S-axis produced least activity in the TA. This was not expected in view of the plantar/dorsiflexion component along this axis. A possible explanation could be found in the foot positioning on the balance board. When the foot is placed in the middle of the board, the axis underneath is situated slightly anterior to the ankle joint. This creates an external moment pushing the ankle towards dorsiflexion which likely demands higher muscle activity of the gastrocnemius muscle to maintain the foot in a neutral position, and less activity of the TA. Finally, it was postulated that exercising along the S-axis would evoke the highest activation levels in the

MG and LG. The S-axis creates a plantar/dorsiflexion motion, which is concordant with the primary plantar flexion function of the gastrocnemius muscle.¹ The MG was indeed more active along this axis compared to the ST-, F- and D-axis. This muscle is least active along the F-axis, where no plantar/dorsiflexion is created. Furthermore, the MG also showed high activity along the ST-axis which fits with the inversion function of the MG on the calcaneus.¹ For the LG, however, lower muscle activity was noted when exercising along the S-axis. This was not expected and an immediate explanation for this result remains unclear. It is important to note for this muscle that highest muscle activity levels were observed when exercising along the D-axis. This does concur with the plantar flexion/eversion moment of the LG on the calcaneus.¹

Remarkably, variation in the magnitude of muscle activity levels as a measure for modulation showed almost exactly the same results as did the magnitude of the muscle activity levels itself. Only for the PL, the comparison of modulation level between the F- and D-axis did not reach the significance level ($p=0.060$), and for the LG between the F- and ST-axis ($p=0.996$) compared to magnitude results. In general, however, one might postulate that also modulation in muscle activity is highest mainly when the orientation of the perturbation matches the anatomical function of that muscle. This modulation in muscle activity, next to a sufficient amount, is considered an important mechanism contributing to postural control.^{2, 33} More modulation would entail more active influence on postural stability. A possible explanation for differences in modulation of muscle activity might be the changes in the center of mass (CoM) during reactive balance control¹⁶. Studies have shown that temporal patterns of individual muscles can be modulated based on feedback resulting from CoM kinematics.^{27, 35} In our study, the primary direction of the CoM excursion will normally be orthogonal to the axis of the board and is more or less controlled. These directions of CoM excursion consequently correspond to certain anatomical functions of the ankle stabilizing muscles, apparently facilitating modulation. A high correlation between magnitude and variation in muscle activity levels using an uniaxial balance board may therefore be rational.

The uniaxial balance board is a commonly used device in the clinical practice for balance training, but up to now scientific research on muscle activation levels depending on foot orientation was lacking. As mentioned before, it has been suggested that higher muscle activation levels may result in a quicker return to preinjury activity level⁷ and that the magnitude of muscle activity levels depends on the stability of the used material.³⁴ Various studies have compared muscle activity levels of the lower leg muscles during exercises using different materials. Blackburn

et al. reported that using special exercise sandals during single leg stance produced equal or even higher muscle activity levels in the PL, TA and LG than single leg stance on a foam pad (respectively 48%, 60%, 54% higher) or T-band kicks in the frontal (respectively 32%, 32%, 22% higher) or sagittal plane (respectively 27%, 27%, 22% higher).⁵ Bellew et al. found higher muscle activity levels in the PL during a 'quarter heel raise' (28% higher) and a 'band heel raise' (40.5% higher) compared to a conventional ankle eversion exercise.⁴ In addition, Cordova et al. found higher muscle activity levels for the PL up to 47%, for the TA up to 74%, and for the MG up to 44%, in favor of T-band kicks compared to SLS on a firm surface. They also found small differences between single leg stance, single leg stance on a trampoline, single leg stance with perturbations, and T-band kicks.⁷ Our results are not based on different levels of instability of the material used, but based on foot orientation in relation to the axis of motion. Our results indicated higher muscle activity levels for the PL of up to 24%, for the TA up to 18%, for the MG of up to 25% and for the LG of up to 22% depending on the foot orientation on the balance board, favoring particular foot orientations for targeting specific ankle stabilizing muscles.

Whilst in the above we focus on increasing muscle activations in general, one needs to be cautious with only targeting increased muscle activity levels. It is important always to consider a balance of agonist-antagonist co-activations.⁵ Increased muscle activity may not be beneficial for every injury mechanism. For example, when using exercise sandals during functional movements Blackburn et al. found higher activity levels for both the TA and PL.⁵ They however found a relative increase in TA muscle activity that was significantly higher than the increase in PL muscle activity during single leg stance and 'high knees'. The latter training modalities may therefore result in disproportionate invertor strength gains compared to evertor strength gains, and may in fact predispose the ankle for inversion injury.⁵ The uniaxial balance board does not have this similar problem. Its single axis of motion allows the therapist to focus exercises on challenging specific agonist-antagonist muscle function during rehabilitation. This reduces the likelihood of creating pathological imbalances between agonist and antagonist muscle groups. Therefore, using an uniaxial balance board, especially in the beginning of rehabilitation, might address the intended muscles better in terms of activation. Afterwards, progression can be made to multidirectional unstable devices, which represents more complex and functional exercises.

The usefulness of balance training in prevention of ankle sprains and treatment of for example chronic ankle instability has been demonstrated in various studies.^{11, 17, 23, 25, 28, 30, 31} Chronic ankle instability has been associated with a delay in peroneal reaction time and an

increase in postural sway.^{21, 22} Studies have tried to enhance peroneal reaction time by performing balance training in healthy subjects and subjects with a history of an ankle sprain, but found no decrease in the reaction time. These studies used an ankle disc for the balance training, which is a multidirectionally unstable device.^{25, 29} It would be interesting to investigate if the use of a uniaxial balance board could indeed induce an improvement in peroneal reaction time, when focusing on the PL by exercising with a foot orientation along the F-axis. This axis creates a similar movement in the ankle joint as the devices developed for simulating an ankle sprain. Our results show that exercises along this axis evoked the highest activation levels in PL, so that specific training along these axes might therefore have improved benefits over training with multidirectionally unstable devices. Also evident improvements in postural control through balance training have been demonstrated.^{9, 13} The working mechanisms, however, remain unclear. A study by Sefton et al postulates that single leg balance protocols on unstable surfaces such as foam, ankle discs, trampolines and wobble boards improve somatosensory input.²⁸ Other authors also found improvements in the non-trained contralateral side indicating an important transfer of training effects through training the central nervous system.⁹ The uniaxial balance board would allow a more focused approach for training somatosensory mechanisms associated with specific anatomical function and aid in gaining a further understanding of transferability of training effects in the context of improving postural control. Further research is needed.

This study focused on healthy subjects for baseline data registration. The muscle activation pattern of healthy subjects is believed to react to the motion provoked by the balance board, whereas patients might produce higher overall cocontractions to protect the ankle joint in any unstable task, independent of the specific axis of rotation. Therefore a healthy population was chosen as it was expected to provide clearer net effects of foot orientation on specific muscle activation levels. Further research will be necessary on patient populations, e.g. subjects with chronic ankle instability, to be able to extrapolate the results of this study. In addition, although we can say for each muscle which axis is the most provocative, our study did not allow to determine which of the muscles is the most active during exercise along the different axes. Normalization to a reference muscle activation level, such as Maximum Voluntary Contractions (MVC's) would have been needed. The reliability of such reference measurements has, however, been questioned and requires further study.⁶ This was beyond the scope of our study. Furthermore, localization of active motor units during standing is divided over the whole muscle. Electrode placement might influence activity registration.³² We used the universally accepted

SENIAM guidelines for electrode placement. Visual detection was used to define the periods in which subjects were balancing. The use of pressure switches, e.g. on the rim of the balance board, could increase the accuracy for defining these periods. Future work could also add further insight by including assessment of joint kinematics to be able to link muscular activation levels to the associated motion. Eventually though, our study was meant to provide an initial insight in the specificity of muscle activation levels for different foot orientations on the uniaxial balance board, and its findings can inform the design of intervention studies which for example evaluate the effects of balance training programs on neuromuscular control in patient populations.

Conclusion

The main goal of balance training is regaining a normal neuromuscular control to a functional level by maximally stimulating the muscle activity levels and modulation of the ankle stabilizing muscles. Muscle activity facilitation on a uniaxial balance board can be influenced according to the orientation of the foot in relation to the rotational axis of the device. This information can be used in the clinical practice where the benefits of uniaxial balance board training can be applied when exercises often have to be adapted to the specific needs of the individual patient.

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References

- (1) Arndt A, Bruggemann GP, Koebke J, Segesser B. Asymmetrical loading of the human triceps surae: II. Differences in calcaneal moments. *Foot Ankle Int* 1999;20(7):450-455.
- (2) Asai Y, Tasaka Y, Nomura K, Nomura T, Casadio M, Morasso P. A model of postural control in quiet standing: robust compensation of delay-induced instability using intermittent activation of feedback control. *PLoS One* 2009;4(7):e6169.
- (3) Ashton-Miller JA, Wojtys EM, Huston LJ, Fry-Welch D. Can proprioception really be improved by exercises? *Knee Surg Sports Traumatol Arthrosc* 2001;9(3):128-136.
- (4) Bellew JW, Frilot CF, Busch SC, Lamothe TV, Ozane CJ. Facilitating activation of the peroneus longus: electromyographic analysis of exercises consistent with biomechanical function. *J Strength Cond Res* 2010;24(2):442-446.
- (5) Blackburn JT, Hirth CJ, Guskiewicz KM. Exercise Sandals Increase Lower Extremity Electromyographic Activity During Functional Activities. *J Athl Train* 2003;38(3):198-203.
- (6) Clarys JP. Electromyography in sports and occupational settings: an update of its limits and possibilities. *Ergonomics* 2000;43(10):1750-1762.
- (7) Cordova M, Jutte L, Hopkins J. EMG comparison of selected ankle rehabilitation exercises. *J Sport Rehab* 1999; 8: 209-218.
- (8) Freeman MA, Dean MR, Hanham IW. The etiology and prevention of functional instability of the foot. *J Bone Joint Surg Br* 1965;47(4):678-685.
- (9) Gauffin H, Tropp H, Odenrick P. Effect of ankle disk training on postural control in patients with functional instability of the ankle joint. *Int J Sports Med* 1988;9(2):141-144.
- (10) Hertel J. Functional Anatomy, Pathomechanics, and Pathophysiology of Lateral Ankle Instability. *J Athl Train* 2002;37(4):364-375.
- (11) Hupperets MD, Verhagen EA, van Mechelen W. The 2Bfit study: is an unsupervised proprioceptive balance board training programme, given in addition to usual care, effective in preventing ankle sprain recurrences? Design of a randomized controlled trial. *BMC Musculoskelet Disord* 2008;9:71.
- (12) Khin MH, Ishii T, Sakane M, Hayashi K. Effect of anesthesia of the sinus tarsi on peroneal reaction time in patients with functional instability of the ankle. *Foot Ankle Int* 1999;20(9):554-559.
- (13) Kidgell DJ, Horvath DM, Jackson BM, Seymour PJ. Effect of six weeks of dura disc and mini-trampoline balance training on postural sway in athletes with functional ankle instability. *J Strength Cond Res* 2007;21(2):466-469.
- (14) Laudner KG, Koschnitzky MM. Ankle muscle activation when using the Both Sides Utilized (BOSU) balance trainer. *J Strength Cond Res* 2010;24(1):218-222.
- (15) Lephart SM, Pincivero DM, Rozzi SL. Proprioception of the ankle and knee. *Sports Med* 1998;25(3):149-155.
- (16) Macpherson JM, Horak FB, Dunbar DC, Dow RS. Stance dependence of automatic postural adjustments in humans. *Exp Brain Res* 1989;78(3):557-566.
- (17) Matsusaka N, Yokoyama S, Tsurusaki T, Inokuchi S, Okita M. Effect of ankle disk training combined with tactile stimulation to the leg and foot on functional instability of the ankle. *Am J Sports Med* 2001;29(1):25-30.

- (18) Mattacola CG, Dwyer MK. Rehabilitation of the Ankle After Acute Sprain or Chronic Instability. *J Athl Train* 2002;37(4):413-429.
- (19) McCullough MB, Ringleb SI, Arai K, Kitaoka HB, Kaufman KR. Moment arms of the ankle throughout the range of motion in three planes. *Foot Ankle Int* 2011;32(3):300-306.
- (20) Michell TB, Ross SE, Blackburn JT, Hirth CJ, Guskiewicz KM. Functional balance training, with or without exercise sandals, for subjects with stable or unstable ankles. *J Athl Train* 2006;41(4):393-398.
- (21) Mitchell A, Dyson R, Hale T, Abraham C. Biomechanics of ankle instability. Part 1: Reaction time to simulated ankle sprain. *Med Sci Sports Exerc* 2008;40(8):1515-1521.
- (22) Mitchell A, Dyson R, Hale T, Abraham C. Biomechanics of ankle instability. Part 2: Postural sway-reaction time relationship. *Med Sci Sports Exerc* 2008;40(8):1522-1528.
- (23) Mohammadi F. Comparison of 3 preventive methods to reduce the recurrence of ankle inversion sprains in male soccer players. *Am J Sports Med* 2007;35(6):922-926.
- (24) Olsen OE, Myklebust G, Engebretsen L, Holme I, Bahr R. Exercises to prevent lower limb injuries in youth sports: cluster randomised controlled trial. *BMJ* 2005;330(7489):449.
- (25) Osborne MD, Chou LS, Laskowski ER, Smith J, Kaufman KR. The effect of ankle disk training on muscle reaction time in subjects with a history of ankle sprain. *Am J Sports Med* 2001;29(5):627-632.
- (26) Rockar PA, Jr. The subtalar joint: anatomy and joint motion. *J Orthop Sports Phys Ther* 1995;21(6):361-372.
- (27) Safavynia SA, Ting LH. Task-level feedback can explain temporal recruitment of spatially fixed muscle synergies throughout postural perturbations. *J Neurophysiol* 2012;107(1):159-177.
- (28) Sefton JM, Yarar C, Hicks-Little CA, Berry JW, Cordova ML. Six weeks of balance training improves sensorimotor function in individuals with chronic ankle instability. *J Orthop Sports Phys Ther* 2011;41(2):81-89.
- (29) Sheth P, Yu B, Laskowski ER, An KN. Ankle disk training influences reaction times of selected muscles in a simulated ankle sprain. *Am J Sports Med* 1997;25(4):538-543.
- (30) van der Wees PJ, Lenssen AF, Hendriks EJ, Stomp DJ, Dekker J, de Bie RA. Effectiveness of exercise therapy and manual mobilisation in ankle sprain and functional instability: a systematic review. *Aust J Physiother* 2006;52(1):27-37.
- (31) Verhagen E, van der Beek A, Twisk J, Bouter L, Bahr R, van MW. The effect of a proprioceptive balance board training program for the prevention of ankle sprains: a prospective controlled trial. *Am J Sports Med* 2004;32(6):1385-1393.
- (32) Vieira TM, Loram ID, Muceli S, Merletti R, Farina D. Postural activation of the human medial gastrocnemius muscle: are the muscle units spatially localised? *J Physiol* 2011;589(Pt 2):431-443.
- (33) Vieira TM, Loram ID, Muceli S, Merletti R, Farina D. Recruitment of motor units in the medial gastrocnemius muscle during human quiet standing: is recruitment intermittent? What triggers recruitment? *J Neurophysiol* 2012;107(2):666-676.
- (34) Wahl MJ, Behm DG. Not all instability training devices enhance muscle activation in highly resistance-trained individuals. *J Strength Cond Res* 2008;22(4):1360-1370.
- (35) Welch TD, Ting LH. A feedback model reproduces muscle activity during human postural responses to support-surface translations. *J Neurophysiol* 2008;99(2):1032-1038.

- (36) Wester JU, Jespersen SM, Nielsen KD, Neumann L. Wobble board training after partial sprains of the lateral ligaments of the ankle: a prospective randomized study. *J Orthop Sports Phys Ther* 1996;23(5):332-336.
- (37) Wikstrom EA, Tillman MD, Chmielewski TL, Cauraugh JH, Borsa PA. Dynamic postural stability deficits in subjects with self-reported ankle instability. *Med Sci Sports Exerc* 2007;39(3):397-402.
- (38) Winter DA. Human balance and posture control during standing and walking. *Gait Posture* 1995.

The influence of balance surface on ankle stabilizing muscle activity in subjects with chronic ankle instability

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Abstract

Objective: To evaluate the effect of surface type on muscle activity of ankle stabilizing muscles in subjects with chronic ankle instability.

Methods: 28 subjects with CAI and 28 healthy controls performed a barefooted single legged stance on four different surfaces. Muscle activity of the mm. peroneus longus(PL)/brevis, tibialis anterior (TA), gastrocnemius medialis was registered using surface EMG. A General Linear Model was used to explore differences in muscle activity between subjects with CAI and controls, and the effect of surface type on muscle activity levels within subjects with CAI.

Results: No differences were found between subjects with CAI and healthy controls. Within subjects with CAI, balancing along a frontal axis and on the BOSU evoked overall highest muscle activity level and the firm surface the least. The firm surface showed lowest TA/PL ratio, followed by balancing along a frontal axis and on the Airex.

Conclusions: Clinicians can use these findings to gradually progress in difficulty level during balance training. To maximally focus on the peroneus longus, with a low TA/PL ratio, exercising on a uni-axial wobble board with the axis orientated parallel underneath the foot can be advised.

Introduction

Balance training is by far the most commonly implemented component of a rehabilitation protocol for chronic ankle instability (CAI). The idea behind this is that subjects with CAI suffer from an impaired neuromuscular control¹⁴, which in normal conditions can be defined as the subconscious activation of dynamic restraints occurring in preparation for and in response to joint motion and loading.²⁵ This impaired neuromuscular control is believed to be a consequence of damage to the mechanoreceptors as a result of sustained ankle sprains, referred to as partial deafferentation.^{13, 19} In addition to afferent input, changes in central processing and alpha motoneuron pool excitability (efferent output) also contribute to general neuromuscular impairment¹⁵. This impairment leads in turn to repetitive episodes of giving way and even ankle sprains, and is consequently considered an important underlying mechanism for chronic ankle instability.

The primary aim of balance training is regaining a normal functional level of neuromuscular control around the ankle joint. Studies have indicated that balance training may very well influence afferent input, result in changes in the sensory cortex, and might as well augment motoneuron pool excitability.^{2, 27} Prospective studies have shown that balance training effectively reduces the risk of sustaining an ankle sprain.^{16, 31} However, not all balance training studies have demonstrated improvement of functional outcome parameters as postural control in subjects with CAI.²² A possible explanation is the large variety of balance training protocols and the fact that it is not known which exercises best serve the rehabilitation goals.

At this moment, no studies have evaluated the effect of balance surface type on muscle activity levels in subjects with CAI. However, it has been postulated that maximally stimulating muscle activity levels is expected to accelerate the rehabilitation process to pre-injury functional levels.⁶ Current knowledge on the influence of commonly used balance equipment on muscle activity levels is based on studies including predominantly healthy subjects.^{3, 4, 6, 32} In addition, most balance protocols use unstable devices without control over the direction in which the ankle is challenged. This reflects a functional situation as one has to be able to stabilize the ankle joint independent of triggering direction. However, in a progressive treatment protocol, it might be desirable to specifically focus at resolving deficits of specific ankle stabilizing muscles, especially in the early stages of rehabilitation, e.g. targeting the peroneus longus in subjects with CAI. To make a clear statement, however, research is lacking on the effect of surface types on muscle activation levels in subjects with CAI.

The first objective of this study was to investigate if there were differences in muscle activity levels of ankle stabilizing muscles during a single-legged balance protocol on various surfaces between subjects with CAI and healthy controls. Secondly, the influence of surface type on these muscle activity levels was assessed in subjects with CAI. As surface types, both multidirectional unstable devices as well as different foot positions on a uni-axial balance board were tested.

Methods

Subjects

A total of 56 subjects, consisting of 28 subjects with CAI and 28 healthy controls volunteered to perform a single legged balance protocol (table 1). Subjects with CAI had to meet all of the following inclusion criteria: a history of a severe ankle sprain resulting in limitations in participation for at least 3 weeks; episodes of giving way; repetitive ankle sprains; feelings of instability and weakness around the ankle joint. Healthy control subjects reported no history of an ankle sprain in the past. Overall, subjects had to be recreationally active defined by a minimum of 1.5 hours of cardiovascular activity per week. Exclusion criteria were ankle fracture or surgery, lower limb complaints at the moment of testing (not related to CAI), and equilibrium disorders. This study was approved by the ethics committee and all subjects provided informed consent.

Table 1. Population characteristics

	CAI (n=28)	Control (n=28)
Age (yrs)	20.3 (1.8)	20.3 (1.8)
Height (m)	1.71 (0.7)	1.72 (0.6)
Weight (kg)	63.4 (6.5)	62.6 (7.5)
BMI	21.6 (1.7)	21.2 (2.3)
FADI	90.6 (5.8)	100.0 (0.2)*
FADI-S	76.7 (12.7)	99.6 (1.8)*
CAIT	14.8 (3.8)	29.7 (0.9)*
# sprains	7.8 (6.4)	N/A
Time to last sprain (months)	5.2 (6.3)	N/A
Orthotics (tape/brace) during sports	19/28	0/28
Insoles	12/28	7/28

BMI=Body Mass Index; FADI=Foot and Ankle Disability Index; FADI-S=Foot and Disability Index Sports subscale; CAIT=Cumberland Ankle Instability Tool; * signifies significant group difference with $p<0.001$

Procedure

Anthropometric data and medical history were collected for all subjects. In addition, the Foot and Ankle Disability Index (FADI), its sports subscale (FADI-S), and the Cumberland Ankle Instability Tool were completed for group descriptive purposes. All subjects were tested unilaterally. For subjects with CAI, the unstable ankle was tested and in case of bilateral instability, the most unstable ankle based on subject indication was included. The healthy controls were matched to the subjects with CAI based on height and body weight. Subsequently, leg dominance was taken into account, i.e. if the dominant leg of the subject with CAI was screened also the dominant leg for the matched control was tested and vice versa.

Muscle activity of the m. tibialis anterior, m. peroneus longus/brevis and m. gastrocnemius medialis/lateralis were registered using surface electromyography at 1000Hz (Myosystem 1400A, Noraxon U.S.A. Inc, Scottsdale, Arizona 85254, U.S.A.). In preparation, the skin was clean-shaven, scrubbed and degreased using ether to reduce skin impedance. Disposable bipolar Ag/AgCl surface electrodes with conducting gel and 2cm diameter were placed with an inter-electrode distance of 2 cm center-to-center and parallel to the muscle fibers according to SENIAM guidelines (www.seniam.org). Signal quality was checked and a baseline rest signal lower than 10 mV was required. Amplifiers were taped onto the lower leg and all wires were fixated by means of a circular gauze to reduce the possibility for motion artifact. Subsequently, three maximal voluntary contractions (MVC) recordings for all registered muscles were performed.

The balance protocol consisted of a barefooted single legged stance on four different surfaces, including a flat surface, an Airex foam pad, a Both Sides Up ball (BOSU) and a custom made uniaxial balance board. The wobble board surface was 40 by 40cm with 2 identical segments of a circle underneath creating the axis of rotation (chord length=28cm, segment height=8cm, segment width=4.5cm). Two foot positions were marked on the uniaxial balance board. The first foot orientation was aligned with the frontal axis of the foot (=WobF) inducing instability in the frontal plane (inversion/eversion). The second foot orientation was in alignment with a diagonal foot axis (=WobD), 45° externally rotated from the frontal axis and creating a plantarflexion/eversion and dorsiflexion/inversion motion. The wobble board was tested on subjects with CAI to make sure it was possible to maintain balance for 5'' without touching the ground with the rim of the board. In general, subjects had to maintain a single legged stance with the knee of the tested leg slightly flexed (knee above the toes, based on visual inspection by the researcher). The hands had to be kept on the hips and subjects had to focus on a mark on the wall at eye height. After a practice trial, the balance exercise was

repeated until 3 successful balancing trials of 5 s were performed on each surface. A trial was discarded if subjects did not keep their hands on their hips, if the balancing foot shifted, if the contralateral foot touched the ground, or if both legs were pushed together for balance. A rest period of 30 s was foreseen between trials and of 1 min 30 s between surface types. The order of the surfaces was randomized and counterbalanced between groups.

Data processing and analysis

MyoResearch 3.4.5. Master Edition (Noraxon U.S.A. Inc, Scottsdale, Arizona 85254, U.S.A.) was used for the processing of the EMG data. The raw data of the EMG signals were full-wave rectified and smoothed using a root mean square with moving average window of 100 ms. The mean EMG value was determined over every 5 s balancing interval and subsequently the mean of the three trials on every individual surface type was calculated. For every muscle these values were then normalized to the respective highest MVC value of the three trials. In addition to individual mean muscle activity levels, the tibialis anterior/peroneus longus ratio (TA/PL ratio) was calculated.

Statistical analysis was performed with SPSS 22 (SPSS Inc., Chicago, Illinois 60606, U.S.A.). For the first research question, differences in muscle activity levels by muscle on the various surfaces between study groups were evaluated using mixed model analyses to analyze interaction effect, i.e. surface*group. In case of a significant interaction effect, multiple pairwise comparisons with a Holm-Bonferroni correction were performed. Secondly, within the CAI group, mixed model analysis was performed for each individual muscle and the TA/PL ratio to assess the effect of surface on muscle activity levels. For the post-hoc multiple pairwise comparisons, a Holm-Bonferroni correction was again performed. Significance levels were set at $p < 0.05$.

Results

CAI vs CON

Only for the medial gastrocnemius a significant interaction effect was found between surface and group ($p = 0.007$). However, post hoc pairwise comparisons indicated no significant difference in muscle activity levels for the different surfaces between subjects with CAI and healthy controls. Mean muscle activity levels are presented in table 2.

Tabel 2. Mean normalized muscle activity (%) and standard deviations on different surface types for both groups

	MG		TA		PL		PB	
	CAI	CON	CAI	CON	CAI	CON	CAI	CON
Firm	20.2 (11.8)	21.5 (12.3)	15.3 (10.5)	19.2 (13.1)	33.1 (13.8)	34.4 (19.2)	27.0 (11.8)	27.7 (14.8)
Airex	29.1 (16.6)	31.9 (17.1)	28.9 (13.7)	39.5 (27.1)	44.8 (14.3)	50.7 (23.9)	45.7 (17.8)	51.6 (25.2)
BOSU	43.8 (22.6)	36.4 (16.7)	46.5 (26.5)	53.6 (24.4)	59.8 (25.0)	66.3 (29.4)	66.4 (18.3)	70.0 (31.6)
WobF	38.9 (21.9)	29.4 (13.5)	43.0 (22.9)	44.8 (23.0)	66.0 (29.8)	64.9 (30.5)	68.2 (20.6)	64.2 (26.5)
WobD	41.1 (26.7)	35.4 (12.2)	41.2 (32.2)	43.4 (22.4)	44.6 (17.6)	48.8 (14.3)	45.5 (17.9)	50.2 (22.0)

MG=Medial Gastrocnemius; TA=Tibialis Anterior; PL=Peroneus Longus; PB=Peroneus Brevis; CAI=subjects with chronic ankle instability; CON=healthy controls

Surface type within CAI

Mixed model analysis showed significant differences in muscle activation according to the surface for all muscles tested ($p < 0.001$). The pairwise comparison results are presented in table 2. Overall, the single legged stance on a firm surface evoked significantly lower muscle activity levels for all muscles and had a significantly lower TA/PL ratio compared to the other surface types. The results of the influence of surface type on muscle activity levels are described below without further reference to the firm surface results. A comprehensive visual overview of the impact of surface on activity levels of all tested muscles is given in Figure 1.

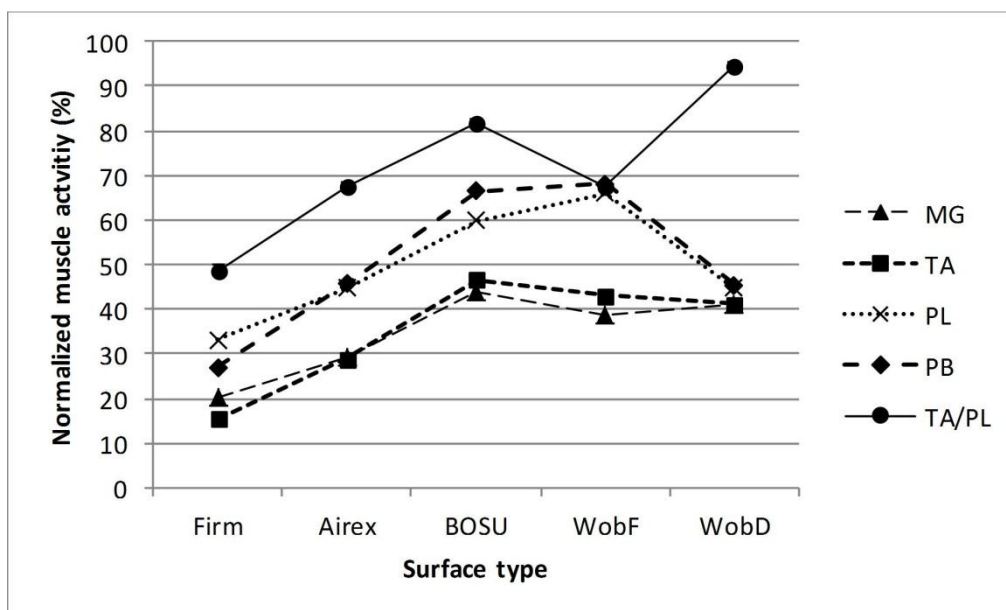


Figure 1. Normalized muscle activity levels and TA/PL ratio on the various surfaces. MG=medial gastrocnemius; TA=tibialis anterior; PL=peroneus longus; PB=peroneus brevis; WobF=wobble board along frontal axis; WobD=wobble board along diagonal axis.

Effect surface on individual muscle activity

Results for PL and PB were similar. Both muscles displayed significantly higher activation levels when balancing on the WobF and the BOSU compared to balancing on the WobD and the airex pad. There was no significant difference in muscle activity between the WobF and BOSU, and between the WobD and Airex pad.

Muscle activation levels of the TA were significantly higher when exercising on the BOSU and the WobF compared to balancing on the Airex pad. There was no significant difference in muscle activation levels between the BOSU, WobF and WobD, and between the WobD and Airex pad.

Table 2 shows significantly higher muscle activation levels in the MG when exercising on the BOSU, WobD and WobF compared to balancing on the Airex pad. There was no significant difference in muscle activation levels between the BOSU, WobF and WobD.

Effect surface on TA/PL ratio

The TA/PL ratio was significantly lower when balancing on the WobF and Airex pad compared to the WobD. Balancing on the WobF and Airex pad also displayed a lower TA/PL ratio compared to the BOSU, although the corrected p-value barely exceeded significance level for the Airex pad comparison (respectively $p=0.046$ and $p=0.054$). There was no significant difference between the WobF and Airex pad and between the BOSU and WobD.

Discussion

Balance training is daily practice in the treatment of CAI, although the effect of surface type on muscle activation levels and TA/PL ratio in this patient population was unknown as for now. The results of our study indicated that the effect of surface type on muscle activity levels of the peroneus longus/brevis, tibialis anterior and gastrocnemius medialis is not different between a healthy control group and subjects with CAI. Furthermore, within the CAI group, the BOSU and WobF evoked overall largest muscle activity levels. In addition, the WobF generated a lower TA/PL ratio. These insights may be helpful in designing balance training programs for subjects with CAI.

We found no differences between the healthy controls and subjects with CAI regarding muscle activity levels evoked by the different surface types. This was somewhat unexpected in view of the reported neuromuscular dysfunctions related to CAI. Several studies showed e.g. a decreased peroneus longus activity in subjects with CAI during gait, side cutting and various

Table 3. Results of the post hoc multiple pairwise comparisons with Holm-Bonferroni correction of the muscle activity levels (% normalized to MVC) according to the different surface types within 1 muscle

surface	Medial gastrocnemius		Tibialis anterior		Peroneus longus		Peroneus brevis		Ratio TA/PL	
	Mean Diff [95% CI]	P-value	Mean Diff [95% CI]	P-value	Mean Diff [95% CI]	P-value	Mean Diff [95% CI]	P-value	Mean Diff [95% CI]	P-value
Firm-AIR	-8.9 [-13.8,-3.9]	0.006*	-13.6 [-17.8, -9.3]	<0.001*	-11.8 [-15.4, -8.2]	<0.001*	-18.7 [-23.9, -13.5]	<0.001*	-18.8 [-28.1, -21.2]	<0.001*
Firm- BOSU	-23.6 [-30.0,-17.1]	<0.001*	-31.2 [-39.2, -23.2]	<0.001*	-26.7 [-34.3, -19.2]	<0.001*	-39.4 [-44.9, -34.0]	<0.001*	-32.8 [-44.6, -14.9]	<0.001*
Firm-WobF	-18.6 [-25.4, -11.9]	<0.001*	-27.7 [-34.9, -20.4]	<0.001*	-32.9 [-42.1, -23.7]	<0.001*	-41.2 [-48.3, -34.1]	<0.001*	-18.8 [-27.2, -10.4]	<0.001*
Firm-WobD	-20.9 [-28.6, -13.1]	<0.001*	-25.9 [-35.7, -16.0]	<0.001*	-11.5 [-14.8, -8.2]	<0.001*	-18.5 [-23.9, -13.1]	<0.001*	-45.8 [-63.0, -28.9]	<0.001*
AIR-BOSU	-14.7 [-20.1, -9.3]	<0.001*	-17.7 [-26.1, -9.2]	<0.001*	-14.9 [-23.0, -6.9]	0.003*	-20.7 [-27.2, -14.2]	<0.001*	-14.1 [-25.6, -2.6]	0.054
AIR-WobF	-9.8 [-15.5, -4.0]	0.010*	-14.1 [-20.8, -6.4]	0.005*	-21.1 [-30.5, -11.7]	<0.001*	-22.5 [-30.4, -14.6]	<0.001*	0.1 [-8.1, 8.1]	1.000
AIR-WobD	-12,0 [-19.0, -5.0]	0.010*	-12.3 [-22.5, -2.2]	0.076	0.3 [-4.1, 4.6]	0.906	0.2 [-6.1, 6.6]	1.000	-27.0 [-44.1, -10.2]	0.015*
BOSU-WobF	5.0 [-2.1, 12.1]	0.498	3.5 [-6.6, 13.7]	1.000	-6.2 [-17.7, 5.3]	0.566	-1.8 [-9.9, 6.3]	1.000	14.1 [3.3, 24.9]	0.048*
BOSU-WobD	2.7 [-5.4, 10.8]	1.000	5.4 [-6.7, 17.4]	1.000	15.2 [7.3, 23.1]	<0.001*	20.9 [14.3, 27.6]	<0.001*	-13.0 [-31.3, 5.2]	0.314
WobF-WobD	-2.3 [-10.6, 6.0]	1.000	1.8 [-9.8, 13.4]	1.000	21.4 [11.9, 30.9]	<0.001*	22.7 [14.7, 30.7]	<0.001*	-27.1 [-43.6, -10.6]	0.012*

AIR=Airex; WobF=Wobble board along the frontal axis; WobD=Wobble board along the diagonal axis

landing protocols.^{9, 26, 29, 30} Next to this, increased activity levels of the tibialis anterior have been reported during hopping tasks.^{10, 23} These findings are, however, not reflected in the muscle activity levels in our study. A possible explanation might be that our results are not based on functional activities as described above and, moreover, most of the described differences in muscle activity were observed in the preparatory phase before contact reflecting the feedforward muscle activation patterns. This was not considered in the current study, in which only static single legged stance exercises were assessed. When assuming that there is no difference between subjects with CAI and healthy controls in evoked muscle activity levels during static balance training independent of surface type, this means that the results of studies on healthy subjects might be extrapolated to subjects with CAI. Knowledge about the impact of surface type on muscle activity levels from these studies^{3-6, 24, 32} may therefore be used in designing a progressive balance training program for subjects with CAI. Caution is warranted as further research is needed on different surfaces to confirm this hypothesis.

Surface type clearly showed an impact on evoked muscle activity levels during the single-leg balance protocol within the CAI group. For all muscles included, standing on a flat surface produced least muscle activation levels. Both the peroneus longus and brevis displayed higher muscle activation levels on the WobF and the BOSU compared to the WobD and Airex pad. The higher activation on the WobF is to be expected based on the orientation of the axis of the balance board creating an inversion/eversion motion.⁸ Control of this inversion/eversion motion corresponds with the eversion function of the peroneus longus and brevis.²¹ The BOSU, on the otherhand, is a multidirectional device with a demonstrated relatively high overall instability level, represented by higher COP area and average sway velocity compared to e.g. an Airex pad.²⁸ This higher instability level might explain the observed higher muscle activity levels. Also for the tibialis anterior the BOSU, together with the WobF, evoked highest muscle activation levels. Based on results of a previous study, we expected higher tibialis anterior muscle activation levels on the WobD.⁸ There was, however, no significant difference in activation levels between the WobD and all other devices. A possible explanation is that a custom made balance board was used which was less provocative compared to our previous study to ensure subjects with CAI could balance during the requested period of time. Finally, for the medial gastrocnemius highest muscle activity levels were also found on the BOSU, with no difference with the WobD and the WobF. Based on anatomical function¹, we expected lower muscle activity levels on the WobF.⁸ However, these results were not confirmed using our custom made balance board. Exercising on the Airex pad produced lower muscle activity levels, possibly based on the lower sway velocity and COP area as discussed above.

Balance training has been shown to be effective in reducing the incidence of ankle sprains.^{16, 31} One of the main challenges of outlining such a balance training program is to establish a progressive increase in difficulty level by selecting suitable exercises. Several studies have been done comparing activity levels of lower limb muscles using different types of exercises, surfaces, playing with visual control, etc.^{3-6, 24, 32} In rehabilitation, balance training programs should be adapted based on pathology type. CAI has been associated with a decreased function of the peroneus longus muscle.^{7, 9, 17, 18, 29, 30, 33} Therefore, muscle activity of this ankle stabilizing muscle should in the first place be targeted during rehabilitation exercises. Based on their findings, Blackburn et al. emphasized also to consider agonist-antagonist co-activation because of the risk of establishing disproportionate muscle activity gains possibly predisposing the ankle for inversion injury.⁴ Therefore, we calculated also the TA/PL ratio in addition to individual muscle activity levels. Based on our results, the following progressive scheme could be advised for treatment of subjects with CAI. To start, single legged stance on a firm surface evokes overall lowest muscle activity levels and the lowest TA/PL ratio. Subsequently, single legged stance on the Airex pad evokes overall low muscle activity levels and has, together with the WobF, a low TA/PL ratio. Based on muscle activity levels alone of the peroneus longus, exercising on the WobD is equal to exercising on an Airex pad. However, single legged stance on the WobD generates the highest TA/PL ratio (TA 26% vs PL 12% muscle activity increase relative to single legged stance on a firm surface) and is therefore not immediately an exercise of choice. Highest muscle activity levels for the peroneus longus are generated when exercising on the BOSU and the WobF. These exercises can be used to maximally target this ankle stabilizing muscle, based on the surface types compared in this study. When considering the TA/PL ratio, single legged stance on the WobF can be considered the best exercise to target the peroneus longus without possibly establishing disproportionate agonist-antagonist co-activation.

The use of a uni-axial balance board has shown that based on the foot orientation the agonist-antagonist co-activation can be somewhat controlled. Although the WobD did not evoke higher muscle activity levels of the tibialis anterior as expected⁸, the higher TA/PL ratio clearly showed that the tibialis anterior is more targeted than the peroneus longus. Similar findings were noted for the WobF, which evoked high muscle activity levels of the peroneus longus as expected⁸, together with the BOSU. In addition, the WobF clearly showed a lower TA/PL ratio indicating a higher focus on the peroneus longus muscle than on the tibialis anterior compared to the BOSU. In rehabilitation of CAI, this exercise seems to better address the needs of this pathology. Therefore, in clinical practice, initially exercising on a uni-axial balance board should be considered before using high level multidirectional unstable devices to really focus on the intended muscles. Research on functional outcome parameters of these exercises is

required to assess their efficacy. A study by Eisen et al. already attempted to evaluate the effect of 4 weeks multidirectional or uni-axial balance training on the Star Excursion Balance Test (SEBT) in a small sample of healthy college athletes.¹¹ They found no improvement in SEBT of the individual interventions, probably due to low statistical power. Further research in patient populations as CAI is necessary to evaluate the possible added value of uni-axial balance training.

The interpretation of the difficulty level of the included exercises is solely based on the evoked muscle activation levels. To assess the instability level and the direction of the instability, it would be interesting to see the effect of surface type, i.e. uni-axial versus different multidirectional devices, on COP displacement and sway velocity.²⁸ Furthermore, not only static exercises are included in balance training programs as progression is typically made towards more dynamic and functional movements.²⁰ The effect of surface types during these more dynamic and functional exercises have not been assessed yet in CAI. A recent study by Feger et al. did find lower limb muscle activity levels in subjects with CAI compared to several functional exercises such as forward lunges and lateral hops, advocating the implementation of functional exercises into a rehabilitation programs.¹² Further research on the effect of surface type on muscle activity levels in subjects with CAI is warranted.

Conclusion

There is a lack of research on the effect of surface types used on muscle activity levels in subjects with CAI to develop evidence based progressive balance training programs. Our results showed no significant differences between subjects with CAI and healthy controls during static balance exercises on various surfaces. Furthermore, clinicians can use our findings regarding the subjects with CAI to gradually progress in difficulty level based on muscle activity level and agonist-agonist co-activation. To maximally focus on the peroneus longus, with a low TA/PL ratio, exercising on a uni-axial wobble board with the axis orientated parallel underneath the foot can be advised.

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Reference list

- (1) Arndt A, Bruggemann GP, Koebke J, Segesser B. Asymmetrical loading of the human triceps surae: II. Differences in calcaneal moments. *Foot Ankle Int* 1999;20(7):450-455.
- (2) Ashton-Miller JA, Wojtys EM, Huston LJ, Fry-Welch D. Can proprioception really be improved by exercises? *Knee Surg Sports Traumatol Arthrosc* 2001;9(3):128-136.
- (3) Bellew JW, Frilot CF, Busch SC, Lamothe TV, Ozane CJ. Facilitating activation of the peroneus longus: electromyographic analysis of exercises consistent with biomechanical function. *J Strength Cond Res* 2010;24(2):442-446.
- (4) Blackburn JT, Hirth CJ, Guskiewicz KM. Exercise Sandals Increase Lower Extremity Electromyographic Activity During Functional Activities. *J Athl Train* 2003;38(3):198-203.
- (5) Borreani S, Calatayud J, Martin J, Colado JC, Tella V, Behm D. Exercise intensity progression for exercises performed on unstable and stable platforms based on ankle muscle activation. *Gait Posture* 2014;39(1):404-409.
- (6) Cordova M, Jutte L, Hopkins J. EMG comparison of selected ankle rehabilitation exercises. *J Sport Rehab* 1999; 8: 209-218.
- (7) David P, Halimi M, Mora I, Doutrelot PL, Petitjean M. Isokinetic Testing of Evertor and Invertor Muscles in Patients with Chronic Ankle Instability. *J Appl Biomech* 2013.
- (8) De RR, Willems T, De MS, Vanrenterghem J, Roosen P. Foot orientation affects muscle activation levels of ankle stabilizers in a single-legged balance board protocol. *Hum Mov Sci* 2014;33:419-431.
- (9) Delahunt E, Monaghan K, Caulfield B. Changes in lower limb kinematics, kinetics, and muscle activity in subjects with functional instability of the ankle joint during a single leg drop jump. *J Orthop Res* 2006;24(10):1991-2000.
- (10) Delahunt E, Monaghan K, Caulfield B. Ankle function during hopping in subjects with functional instability of the ankle joint. *Scand J Med Sci Sports* 2007;17(6):641-648.
- (11) Eisen TC, Danoff JV, Leone JE, Miller TA. The effects of multiaxial and uniaxial unstable surface balance training in college athletes. *J Strength Cond Res* 2010;24(7):1740-1745.
- (12) Feger MA, Donovan L, Hart JM, Hertel J. Lower Extremity Muscle Activation During Functional Exercises in Patients With and Without Chronic Ankle Instability. *PM R* 2014.
- (13) Freeman MA, Dean MR, Hanham IW. The etiology and prevention of functional instability of the foot. *J Bone Joint Surg Br* 1965;47(4):678-685.
- (14) Hertel J. Functional Anatomy, Pathomechanics, and Pathophysiology of Lateral Ankle Instability. *J Athl Train* 2002;37(4):364-375.
- (15) Hertel J. Sensorimotor deficits with ankle sprains and chronic ankle instability. *Clin Sports Med* 2008;27(3):353-70, vii.
- (16) Hupperets MD, Verhagen EA, van Mechelen W. The 2BFit study: is an unsupervised proprioceptive balance board training programme, given in addition to usual care, effective in preventing ankle sprain recurrences? Design of a randomized controlled trial. *BMC Musculoskelet Disord* 2008;9:71.

- (17) Kavanagh JJ, Bisset LM, Tsao H. Deficits in reaction time due to increased motor time of peroneus longus in people with chronic ankle instability. *J Biomech* 2012;45(3):605-608.
- (18) Konradsen L, Ravn JB. Prolonged peroneal reaction time in ankle instability. *Int J Sports Med* 1991;12(3):290-292.
- (19) Lephart SM, Pincivero DM, Rozzi SL. Proprioception of the ankle and knee. *Sports Med* 1998;25(3):149-155.
- (20) Mattacola CG, Dwyer MK. Rehabilitation of the Ankle After Acute Sprain or Chronic Instability. *J Athl Train* 2002;37(4):413-429.
- (21) McCullough MB, Ringleb SI, Arai K, Kitaoka HB, Kaufman KR. Moment arms of the ankle throughout the range of motion in three planes. *Foot Ankle Int* 2011;32(3):300-306.
- (22) McKeon PO, Hertel J. Systematic review of postural control and lateral ankle instability, part II: is balance training clinically effective? *J Athl Train* 2008;43(3):305-315.
- (23) Monteleone BJ, Ronsky JL, Meeuwisse WH, Zernicke RF. Ankle Kinematics and Muscle Activity in Functional Ankle Instability. *Clin J Sport Med* 2013.
- (24) Muehlbauer T, Roth R, Bopp M, Granacher U. An exercise sequence for progression in balance training. *J Strength Cond Res* 2012;26(2):568-574.
- (25) Riemann BL, Lephart SM. The sensorimotor system, part I: the physiologic basis of functional joint stability. *J Athl Train* 2002;37(1):71-79.
- (26) Santilli V, Frascarelli MA, Paoloni M et al. Peroneus longus muscle activation pattern during gait cycle in athletes affected by functional ankle instability: a surface electromyographic study. *Am J Sports Med* 2005;33(8):1183-1187.
- (27) Sefton JM, Yarar C, Hicks-Little CA, Berry JW, Cordova ML. Six weeks of balance training improves sensorimotor function in individuals with chronic ankle instability. *J Orthop Sports Phys Ther* 2011;41(2):81-89.
- (28) Stanek JM, Meyer J, Lynall R. Single-limb-balance difficulty on 4 commonly used rehabilitation devices. *J Sport Rehabil* 2013;22(4):288-295.
- (29) Suda EY, Amorim CF, Sacco IC. Influence of ankle functional instability on the ankle electromyography during landing after volleyball blocking. *J Electromyogr Kinesiol* 2009;19(2):e84-e93.
- (30) Suda EY, Sacco IC. Altered leg muscle activity in volleyball players with functional ankle instability during a sideward lateral cutting movement. *Phys Ther Sport* 2011;12(4):164-170.
- (31) Verhagen E, van der Beek A, Twisk J, Bouter L, Bahr R, van Mechelen W. The effect of a proprioceptive balance board training program for the prevention of ankle sprains: a prospective controlled trial. *Am J Sports Med* 2004;32(6):1385-1393.
- (32) Wahl MJ, Behm DG. Not all instability training devices enhance muscle activation in highly resistance-trained individuals. *J Strength Cond Res* 2008;22(4):1360-1370.
- (33) Willems T, Witvrouw E, Verstuyft J, Vaes P, De Clercq D. Proprioception and Muscle Strength in Subjects With a History of Ankle Sprains and Chronic Instability. *J Athl Train* 2002;37(4):487-493.

General discussion

The main purpose of this dissertation was to make a valuable contribution to the knowledge on chronic ankle instability (CAI). The research questions we tried to answer were focused both on the underlying mechanisms associated with CAI (*chapter 1, 2 and 3*) and on treatment modalities aiming at improving impairments ascribed to CAI (*chapter 4 and 5*). Although substantial research has endeavored to address these questions, some aspects remain unaddressed or unclear. In addition, we tried to give rationale for developing a progressive balance training protocol as it remains for now unclear which exercises in a balance training program best serve the rehabilitation goals (*chapter 6 and 7*).

Before elaborating on the findings within our specific research question, we believe it is important to situate our research population within the broader spectrum of CAI. As mentioned in the introduction, the Hertel model incorporates two main entities contributing to the development of CAI, namely mechanical instability and functional instability.³⁸ The evolution of this model by Hiller et al. described 7 subgroups within the spectrum of CAI, defining CAI as a pathology that occurs due to recurrent sprains, functional (perceived) instability, mechanical instability or different combinations of these three key components.⁴⁰ Delahunt suggested, however, that mechanical instability alone cannot explain the persistent residual symptoms subsequent to an initial ankle sprain.²¹ Additionally, a conclusive association between ankle laxity and CAI has not been established.³³ Therefore, the International Ankle Consortium has recently issued a position statement on recommended inclusion criteria based on injury history, function and disability. The authors of this position statement argued that mechanical instability outcomes have not been observed consistently in subjects with CAI, supporting the contribution of functional instability, rather than mechanical instability, in defining CAI.³³ Their key recommendations for inclusion criteria entail (1) a history of at least one significant ankle sprain, (2) a history of the previously injured ankle joint giving way, and/or recurrent sprain and/or 'feelings of instability', and (3) a general self-reported foot and ankle function questionnaire. Although our inclusion criteria were set before this position statement, they are to a large extent in line with this position statement as discussed in *chapter 1*. We did, however, not account for the presence of mechanical instability as a potential confounding factor. Outlining these research population characteristics is important to enable comparison with other studies as it has been emphasized that the use of divergent criteria may account for the inconsistencies found in literature. As stated in the introduction, this dissertation addresses three main aims. In this general discussion, the key findings from the different chapters will be further explored.

Underlying biomechanical mechanisms of chronic ankle instability

The first aim of this doctoral dissertation was to improve insight in the underlying biomechanical mechanisms of CAI. Furthering insight in potentially altered motion patterns of subjects with CAI may identify those deflections which could be associated with an ankle sprain event or an episode of 'giving way'. Kinematical deflections are believed to result from spinal and supraspinal mechanisms associated with CAI.³⁹ When considering our first three chapters, **we have identified potential local biomechanical contributors related to the ankle joint. Additionally, we have determined potential non-local contributors (distant from the site of injury) distally at the foot complex, but not proximally at the level of the knee or hip joint.** Furthermore, differences in results described in literature and in our various chapters suggest **findings to be task specific**, rather than generic.

Local contributors

Ankle

The ankle sprain mechanism is associated with plantar flexion, inversion and adduction of the ankle joint.³² A model driven study by Wright et al. showed that an increased plantar flexion position at touch down, more than an inverted position, increases the susceptibility to sustain an ankle sprain.⁹³ In *chapter 3*, however, subjects with CAI displayed **a less plantar flexed position upon impact** at the ankle joint compared to the control group during a side jump and vertical drop, in line with other studies.¹² Bearing the ankle sprain mechanism in mind, subjects with CAI might try to limit plantar flexion at touch down **as a protective strategy**. However, as we argued in *chapter 3*, this 'protective strategy' can at the same time be **counterproductive. The ROM in the sagittal plane was reduced** during the impact phase for both the vertical drop and side jump in subjects with CAI. This **more rigid strategy** might suppress the capacity to react appropriately to external perturbations, as CAI has been associated with neuromuscular control deficits^{25, 70, 74, 75}, and might have a negative influence on vertical impact forces. In fact, our CAI group exhibited **higher loading rates** as a result of both an earlier, as well as a higher peak vertical GRF, during the vertical drop which has been pointed out previously in other studies.^{11, 24} Increased loading rates may very well put a subject at risk for sustaining an injury because of possible limited capacity to absorb this higher loading.

The finding of this decreased plantar flexion angle at the ankle joint might very well not be generic. In *chapter 1*, we did not find a decreased plantar flexion at the ankle joint at touchdown, unlike demonstrated in *chapter 3*. A possible explanation might be found in the **task specific nature of the performed protocol**. When interpreting kinetic and kinematic outcomes, it is important to bear in mind that outcomes may vary depending on the functional task. To illustrate, divergent

biomechanical demands have been demonstrated when comparing 3 different landings tasks in healthy subjects.¹⁷ These differences are probably due to the need to absorb impact forces and, depending on the task, to the need to generate power for a subsequent task. Considering ACL injuries, these authors suggest that differences in potential risk factors portrayed in literature may partly be explained by differences in selected tasks. Therefore, it may not be appropriate to compare results from studies using different landing tasks because any differences found in the results may be masked by task-related differences¹⁷. It has also been emphasized that the specificity of the landing task is important to consider when screening for injury risk factors.¹⁰ In *chapter 1*, subjects performed a forward jump and a side jump over a specific height starting out on both feet followed by a single leg landing, whereas in *chapter 3* the vertical drop and the maximal side jump was performed starting out on the contralateral limb and landing on the tested ankle. These task-related differences might explain the diverging findings on the ankle position.

Frontal plane results at the ankle joint, showed a more everted position in subjects with CAI compared to controls in *chapter 2* and *3*, but not in *chapter 1*. These results do not seem to fit with the ankle sprain mechanism.³² When comparing with limited available literature, some studies did describe a more inverted position of the foot during gait and landing tasks^{13, 23, 25, 29, 53, 58}, other studies did not.^{13, 48, 52, 59} As an explanation for our results, a compensation mechanism trying to avoid excessive inversion has been postulated.⁹⁰ Another possible mechanism could be found in an imbalanced muscle strength ratio around the ankle joint, which could result in an inadequate eccentric control of eversion during dynamic tasks.¹⁹ When overviewing literature on ankle kinematics, **the variability in reported ankle position results may be more important than the actual reported position itself**. As it happens, Kipp et al. and Brown et al. observed **higher inter-trial variability in frontal plane ankle kinematics**, without average angular position differences, in subjects with CAI.^{9, 47} Higher variability in movement patterns has been shown to be related to increased risks of fall in elderly people.³⁶ The higher variability in ankle kinematics might reflect the spinal and supraspinal adaptations associated with CAI.³⁵ Brown et al. indicated that when variability is too great, strength and proprioception may not be enough to overcome injury risk.⁹

When reconciling knowledge from literature with our results on local factors related to the ankle joint, a combination of higher frontal plane movement variability^{9, 47} and impaired neuromuscular control^{25, 70} with a potentially stiffer landing strategy (*chapter 3*) might explain susceptibility for episodes of 'giving way' and ankle sprain events during specific tasks in subjects with CAI.

Non-local contributors

The rationale of evaluating more distal and proximal non-local joints is based on kinetic chain theories. Although non-local factors do not have a direct link with the injury localization, they might very well play an important role in the development of injuries.¹⁴

Foot complex

In *chapter 2* and *3*, multi-segmented foot kinematics were evaluated and discussed during gait and a landing protocol respectively. Morisson and Kaminski⁶⁰ underlined the importance of capturing foot motion to be able to understand lower extremity mechanics and foot-related risk factors for a lateral ankle sprain and chronic ankle instability. Our studies indicated that the use of the multisegmented foot model to evaluate kinematic alterations in subjects with CAI show promising results (*chapter 2* and *3*), while further research is of course warranted as there is currently no literature to compare results with.

In *chapter 2*, the medial forefoot (first ray) showed **an increased inverted position during the mid- and late stance during both walking and running**. This could be associated with an impaired function of the m. peroneus longus (PL) during gait in subjects with CAI.⁷⁰ In addition, **the rearfoot demonstrated a more everted foot position**. It has been stated that a pronated foot reduces the mechanical advantage of the PL, perhaps because in the pronated position the muscle might be slightly shortened.²⁷ During gait, the PL is found to be active in mid- and late stance of a gait cycle⁴², which corresponds with the timing of the observed kinematic differences for the medial forefoot. The described impaired function of the PL could therefore be associated with the higher inversion angle of the medial forefoot in subjects with CAI as described in *chapter 2*. This inverted position of the medial forefoot could be associated with a so-called loose-packed position which reflects a mechanically less stable condition.⁶⁵ However, **during the vertical drop and the side jump in chapter 3, this mechanism was not observed**. This might not be surprising as research has shown that the PL is already more activated in the prelanding phase during a drop landing compared to walking or running conditions.⁵⁶ This could account for the differences in results between the functional tasks, even though an impaired function of the PL has been ascribed to CAI. In *chapter 3*, subjects with CAI also displayed **a more inverted position of the midfoot** throughout the whole impact phase of the side jump compared to controls. As the midfoot fulfills **an important role in coupling rearfoot and forefoot motion**⁵, further research might elucidate the impact of midfoot kinematics observed in the current study by investigating the forefoot and rearfoot coupling in CAI. Other studies have already focused on the shank-rearfoot joint coupling in subjects with CAI, identifying greater combined motion.^{29, 37} Similar studies on the rearfoot-forefoot coupling might be worthwhile. Furthermore,

differences in hallux kinematics have been observed, namely for the vertical drop a more adducted hallux position for subjects with CAI compared to controls. A possible contribution to CAI mechanism remains, however, unclear. Notwithstanding Willems et al. described an increased plantarflexion/dorsiflexion ROM of the hallux to be a risk factor for sustaining an ankle sprain event, we did not observe this increased ROM during our landing tasks.⁹²

These results indicate the possible added value of multi-segmented kinematics in understanding mechanisms associated with CAI. Unlike in chapter 1, we used a liberal approach without correction for the dependent planes of motion in view of the explorative nature of our studies. Future research is necessary to confirm these results and to further elucidate the contribution of intrinsic foot mechanisms in CAI.

Proximal non-local joints

In *chapter 1*, lower limb kinematics of the hip and knee joint of subjects with CAI were evaluated during a sagittal and frontal plane landing task. We did **not identify any significant differences in hip and knee joint kinematics in subjects with CAI**. These results were somewhat unexpected since CAI has been associated with altered supraspinal motor control mechanisms.³⁵ However, as extensively discussed in chapter 1, other available literature also describes divergent results without a clear consensus on the involvement of hip and knee joint kinematics in the mechanism of CAI. Delahunt et al.²⁴ did report less external rotation of the hip joint during a vertical drop in subjects with CAI, arguing possible proximal neuromuscular impairments through central neural adaptations as foundation. Some studies support this theory of proximal neuromuscular impairments. For example, a study by Van Deun et al. demonstrated a delayed muscle onset of the m. gluteus medius and the m. tensor fascia latae while transitioning from a double-leg stance to a single-leg in subjects with CAI.⁸¹ In addition, Webster et al. demonstrated a decreased activation of the m. gluteus maximus during a rotational squat in subjects with CAI compared to a healthy control group.⁸⁷ At the level of the knee, increased muscle activity of the m. rectus femoris and the m. vastus medialis obliquus have been described during landing tasks.^{25, 77} However, **a direct link between such impairments and altered kinematics has not been established yet**. Furthermore, similar to the studies on kinematics, the results on neuromuscular control are not consistent between studies^{24, 25}, again emphasizing **task specific adaptations**.

Our results do **not confirm the involvement of more proximal non-local joint kinematics in the mechanism of CAI**. However, solely based on our study, and in view of described neuromuscular, kinematic and task specific adaptations, we cannot definitively rule out hip and knee joint contribution in a generic context.

Copers

In *chapter 2* and *3*, a copers group was included to further elucidate the mechanism of CAI. Notwithstanding the relative high amount of patients who develop residual symptoms or chronic ankle instability after an acute ankle sprain, some patients return to their preinjury level of functional participation without any negative impact following a sustained sprain. These 'copers' somehow differ from subjects with CAI and identifying these differences might help clarifying the contributing mechanisms to CAI.⁸⁸

Overall, we observed **to a large extent similar kinematic differences between subjects with CAI and copers compared with controls and no differences between the CAI group and copers.** Literature on copers is of yet scarce and a clear statement on kinematic adaptations is prohibited.⁸⁸ When comparing subjects with CAI to copers, both a less plantar flexed⁷ and a more plantar flexed ankle position³⁴ during landings tasks have been described, as well as increased frontal plane ROM⁷, decreased sagittal plane ROM⁷ and a less inverted ankle position.³⁴ The copers in our studies had to have sustained a recent ankle sprain, as we aimed at identifying active coping strategies in the period during which an individual is most susceptible to sustain a resprain. This potentially explains the similar differences between copers and subjects with CAI compared to controls, **representing impairments, due to the recent sprain, that copers are able to compensate while subjects with CAI cannot.** This compensation may be reflected in other factors such as proprioception, postural stability, strength or neuromuscular control, although literature on these parameters regarding copers is limited.⁸⁸ A recent study shows that perception-based outcomes have the greatest ability to discriminate between subjects with CAI and copers.⁸⁹ In agreement, subjects with CAI in our studies scored significantly lower on the Foot and Ankle Disability Index and its sports subscale (FADI and FADI-S) compared to copers. Nevertheless, a few differences have been determined in *chapter 3* regarding our copers group. Unlike the subjects with CAI, the copers had no significantly decreased ROM in the rigid foot and rearfoot during the impact phase compared to the controls. On the contrary, the copers group had **a more dorsiflexed joint angle at the end of the impact phase** for the side jump compared to the controls, indicating **a more closed packed position**, which is considered a locked and therefore stable position of the joint.⁴⁴ **No differences in loading rate** were found between copers and the control group. This could protect them from possible episodes of giving way and ankle sprain events and differentiate the copers from the subjects with CAI.

Conclusion

We have identified task specific biomechanical mechanisms potentially associated with the mechanism of CAI. When considering the entire lower limb, local contributors related to the ankle joint and non-local contributors related to the foot complex have been found. We have not identified any proximal non-local factors at the level of the knee or hip. Subjects with CAI displayed a stiffer landing pattern associated with higher loading rates during a vertical drop, potentially increasing susceptibility to injury. However this finding was not generic for all included landing tasks, emphasizing the observed results to be task specific. Furthermore, exploring multi-segmented foot kinematics may be beneficial in understanding foot mechanisms associated with CAI. Further task specific research is warranted to increase the insight in lower limb kinematics, including foot and ankle kinematics, during functional tasks, and gain a better understanding of underlying mechanisms of CAI.

The effect of treatment modalities on postural control

The treatment of CAI remains quite a challenge for clinicians since the underlying multifactorial mechanism of CAI is still as of yet unclear. Clinicians can use a variety of treatment modalities including mobilization techniques, proprioceptive training, strength exercises, balance training, functional training, and external support in the treatment of CAI. In *chapter 4* and *5*, we evaluated the effect of 2 frequently used treatment modalities on a generally accepted impairment associated with CAI, i.e. impaired postural control. As stated, it is believed that a more stable body results in a reduced incidence of recurrent lower extremity injuries emphasizing that **improving postural control is an important aspect of injury prevention.**⁸³ As treatment modalities, a balance training program (*chapter 4*) and a taping protocol (*chapter 5*) were used. As outcome parameter for our interventions, we chose dynamic postural control, because it has been shown in literature that dynamic assessments of postural control were more consistent at identifying deficits in postural control than static assessments.³⁹ In addition, many ankle sprains occur during a landing task favoring such events as subject for intervention research.³⁰ In general, we did **not find an improvement in dynamic postural control** following our intervention modalities. Both treatment modalities did show their **capacity of improving subjective feelings of stability.** These inconsistencies between subjective and

objective parameters are of interest and might suggest that **other objective parameters should be considered** for teasing out potentially subtle differences following these intervention modalities.

Balance training has been proven to reduce the risk of sustaining an ankle sprain and is a universally accepted rehabilitation modality for the treatment of acute ankle sprains and CAI.^{8, 43, 78, 86} In *chapter 4*, the effect of a common 8-week home-based balance training protocol was assessed on postural control in subjects with CAI during a vertical drop. Our results indicated **no effect of our 8-week balance training protocol on the Dynamic Postural Stability Index (DPSI) and its subcomponents**. As discussed in *chapter 4*, a possible explanation might be found in the **specificity of the balance training program** used in our study. We integrated single leg stance and dynamic balance exercises with traditional progression by means of visual control, surface material and variation in arm position.⁵⁵ Until now, **it remains unclear which exercises best serve the rehabilitation purposes**. Overall, our program included mainly static exercises, gradually increasing in difficulty. After 2 weeks, subjects started to perform balance exercises during dynamic tasks. However, the training program might be not sufficiently specific to improve postural balance during the investigated landing tasks. It has been shown that balance training has an effect on corticospinal activation and that these changes **are task specific**.^{72, 76} Possibly, more dynamic exercises simulating **sport specific movements** are needed in order to obtain training effect. Although the importance of sport specific exercises, we strongly believe these exercises alone are insufficient to address the muscular impairments associated with CAI during functional tasks. Exercises should be implemented to focus on e.g. the PL to activate this ankle stabilizing muscle in less complex exercises before starting the sport specific exercises during which the impairment is present. Therefore, in *chapter 6* and *7*, we tried to identify those **exercises which can be used to focus on specific muscles in subjects with CAI** and that we believe should be integrated in balance training protocols. This will be discussed further on.

In *chapter 5*, a similar evaluation was made using a taping protocol as intervention modality for improving postural control. The **taping procedure showed to be effective in altering foot position at landing and limiting ROM** during impact. However, **no effect was found of the taping procedure on postural control** during a forward and side jump protocol. As postulated explanation, the tape might limit the possibility of using an efficient ‘ankle strategy’ to maintain balance by performing pro- and supination motions. Subjects might therefore be compelled to use **a less efficient ‘hip strategy’**, potentially leading to higher shear forces.⁶⁷ Therefore, it might not be surprising that postural control based solely on GRF does not show a positive effect of the use of tape. If taping does not have a positive influence on postural stability, there must be some other explanation for the lower incidence rates for reoccurrence of acute lateral ankle sprains.^{57, 62}

Although we did not observe an effect on postural control, both treatment protocols did show their **capacity of improving subjective feelings of stability** in subjects with CAI. This can be

considered an important treatment effect which should not be underestimated because the perception of a patient or athlete may very well influence the effectiveness of the treatment modality in preventing injury.⁷¹ However, it might be necessary to treat these positive outcomes carefully as no objective changes have been detected. A subject may develop a false feeling of stability putting him/her at risk for effectively sustaining an ankle sprain. Therefore, it is important to objectify the effect of these treatment protocols.

As aforementioned, **both balance training and taping have shown their capacity at reducing the incidence of ankle sprains.**^{57, 62} This might not be reflected in our postural stability measures which not only look at the impact but also comprises some time after the landing. This might obscure the real effect of the treatment modality on the landing mechanism. A recent study by Liu et al. questions the diagnostic accuracy of the current dynamic postural stability measures, suggesting other measures should be explored.⁵⁴ Therefore, **other parameters should be considered** for teasing out potentially subtle differences. The tape protocol clearly showed in *chapter 5* that it alters landing kinematics. Combining kinematic and kinetic data, e.g. using advanced whole body motion analysis such as induced acceleration analysis might further elucidate the effect of these treatment modalities. This was outside the scope of the current studies, but could be considered in future research. Furthermore, the effect on neuromuscular control before, at and after landing might also increase insight in underlying rehabilitation mechanisms.

Conclusion

Both our balance training program and taping protocol showed their capacity of improving subjective feelings of stability, which can be considered an important treatment effect as this may affect the effectiveness of the treatment modality. However, caution is warranted. After all, both treatment protocols showed no effect on the dynamic postural control measured by means of the DPSI. Since a positive effect of these treatment modalities has been shown on ankle sprains, other parameters should be used to quantify this positive outcome effect.

Rationale for developing a balance training protocol

As aforementioned, balance training protocols are universally accepted as treatment modality for CAI. The main goal of balance training is regaining a normal neuromuscular control around the ankle to a functional level. However, as mentioned in *chapter 4*, it remains as of yet **unclear which exercises included in a balance training protocol best serve the rehabilitations goals**. Nevertheless, this knowledge is important in a progressive treatment protocol as it might be **essential to specifically focus at resolving deficits of specific ankle stabilizing muscles**. Therefore, the goal in *chapter 6* was to establish the effect of foot orientation on a uni-axial balance board on muscle activity levels in healthy subjects. This knowledge was then used in *chapter 7*, in which we compared the effect of various balance devices on muscle activity levels in subjects with CAI. Based on these results we believe we can make sensible suggestions on introducing progression in a balance training protocol.

In *chapter 6*, our study showed that **for each ankle stabilizing muscle there was a specific foot orientation on the balance board which generated higher muscle activation levels** compared to the other orientations in healthy subjects. These results can be to a large extent matched with the primary anatomical function of that muscle. Our study showed **highest muscle activity levels for the PL and the TA respectively when balancing along a frontal axis and a diagonal axis**. Given their effect on frontal plane kinematics, the PL and TA can be considered important ankle stabilizing muscles. Therefore, these 2 foot orientations were used in *chapter 7* for further comparison of muscle activity levels to other balance devices in subjects with CAI.

Knowledge on balance progression based on muscle activity levels, is primarily founded on studies with healthy subjects. As of now, there was no ground of extrapolating these results to subjects with CAI. Our study revealed **no differences in impact of surface type during single leg stance on muscle activity levels of ankle stabilizing muscles between subjects with CAI and healthy controls**. Therefore, we believe that knowledge about the impact of surface type on muscle activity levels from studies using healthy subjects^{3, 4, 6, 15, 61, 85} may very well be used in designing a progressive balance training program for subjects with CAI.

In the second part of *chapter 7*, we compared the effect of a uni-axial balance board and multidirectionally unstable devices. Multidirectionally unstable devices have in common that there is no control over the rotation direction in which the ankle is challenged. Uni-axial balance boards, on the other hand, allow for uni-axial rotational instability which depends on foot orientation on the board. This may be useful when rehabilitation is meant to target specific ankle stabilizing muscles. Our results showed that **by using a uni-axial balance board the agonist-antagonist co-activation can be somewhat controlled based on the foot orientation**. The PL is considered an important muscle in

the mechanism of CAI, based on its anatomical function and since CAI has been associated with a decreased function of the PL.^{19, 24, 46, 51, 74, 75, 91} During rehabilitation exercises muscle activity of this ankle stabilizing muscle should therefore be targeted. Bearing progression in mind, single leg stance on the **firm surface evoked the lowest muscle activity levels and also had the lowest TA/PL ratio.** Next in the progression scheme, both the airex pad and wobble board along the diagonal axis evoked similar activity levels of the PL. However, the TA/PL ratio when balancing on the wobble board along the diagonal axis was highest of all considered surface types and therefore maybe not immediately suitable in the rehabilitation of CAI. The airex pad, on the other hand, showed a low TA/PL ratio comparable with that of balancing on the wobble board along the frontal axis. Finally, both balancing along a frontal axis and on the BOSU evoked highest activity levels in PL. Therefore, both of these exercises could be used for maximally targeting the PL. However, **when considering the TA/PL ratio, the uni-axial balance board (frontal axis) clearly showed a lower ratio compared to the BOSU indicating a better focus on the targeted muscle, i.e. the PL.** These results can be used to outline a progressive balance training protocol. Further research is necessary to establish the efficacy of these progression principles.

Conclusion

When performing single leg balance exercises on a uni-axial balance board, the foot orientation determines which ankle stabilizing muscle is targeted based on anatomical function. Furthermore, we did not observe differences in impact of surface type on muscle activity levels of ankle stabilizing muscles between subjects with CAI and healthy controls, suggesting that extrapolation of results may be possible. Finally, a uni-axial balance board can be used to control the agonist-antagonist co-activation based on the foot orientation. Consequently, to maximally focus on the PL in subjects with CAI with a low TA/PL contraction, exercising on a uni-axial balance board along the frontal axis has been proven the best choice.

Strengths and limitations

This dissertation offers a valuable contribution to further the knowledge on the underlying mechanism and treatment of CAI. In chapter 1, 2, and 3, biomechanical differences between subjects with CAI and controls during functional tasks were evaluated. To analyze the kinematical data we used SPM, enabling continuous statistical analysis of smooth data curves. In addition, we were the first to use a multi-segmented foot model opening a window for insights in intrinsic foot behavior

associated with CAI. In *chapter 4* and *5*, we were the first to evaluate the effect of commonly used treatment modalities on dynamic postural stability during a landing task. Furthermore, in *chapter 6* and *7*, we provided clinicians pretext to design a progressive balance training program which can be adapted to the specific needs of subjects with CAI.

To analyze our kinematical datasets, we chose to implement statistical parametric mapping (SPM). When investigating and processing 3D body segment kinematics, potential risks of bias can arise. Using discrete variables may result in 'regional focus bias', meaning that when only focusing on certain given moments in time, overall maximums or minimums, important curve information is ignored.⁶⁴ It also creates an abstraction when e.g. only working with maximum values, because these results have to be situated within the original curve to understand values. Therefore, discretization can compromise the spatiotemporal integrity of original datasets.⁶³ Furthermore, analyzing kinematic curves discretely by extracting summary metrics from particular points or regions from the whole curve, can have statistical consequences. Pataky, Robinson and Vanrenterghem indicated that through 'post hoc regional focus bias' type I and type II errors might occur, resulting from the failure to consider the entire measurement domain.⁶⁴ SPM creates a framework which allows continuous statistical analysis of, in our studies, smooth 1D data curves. This partially offsets the limitations described above. We strongly believe that the use of SPM results in a more valid analysis of biomechanical datasets.

An important limitation of our research on underlying mechanisms is that the studies had a case-control design, inhibiting statement on causative relationships. To be able to answer the question of a causative relationship, longitudinal prospective research, which incorporates temporality, is necessary.⁶⁶ At this moment prospective research on the development of CAI is limited and should be the focus of future research.⁶⁸

As aforementioned at the beginning of the general discussion, we believe our inclusion criteria for our subjects with CAI to be to a large extent in line with the recent position statement of the International Ankle Consortium.³³ Although not part of the proposed included selection criteria due to the unclear link with CAI, mechanical instability might be considered a confounding factor. In our research we did not account for the possible presence of mechanical instability.

Another limitation is that all studies were performed in a laboratory setting. Therefore, subjects maybe more focused on the task at hand. Subjects with CAI do not experience episodes of giving way continuously, so the execution of these controlled tasks might obscure possible kinematic differences between subjects with CAI and healthy controls or even obscure intervention effects. However, the used research methodology requires specialized equipment inherent to a laboratory setting. Furthermore, all of our studies were performed barefoot. It has been shown that shod versus barefoot landings may alter impact forces that modulate stiffness strategies.⁷³ However, the use of

shoes might be considered an important confounding factor potentially influencing study outcomes. Additionally, the use of the multi-segmented foot model makes wearing shoes impossible.

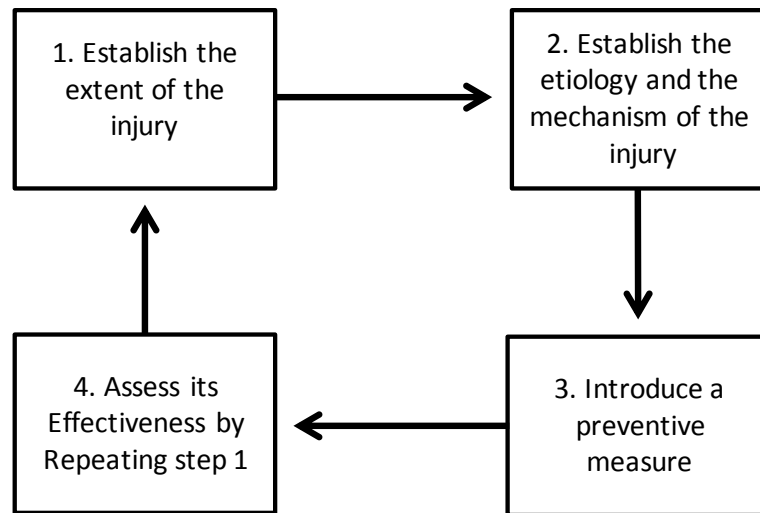
Finally, we only looked at biomechanical factors and postural control as outcome measures for our first two aims. However, an important role has been ascribed to an impaired neuromuscular control, comprising both the feedback and feedforward mechanism.³⁹ Additional registration of muscle activity could have been advantageous, potentially providing more insight in the observed results of the used outcome measures. In the third part of this dissertation we did use muscle activity to establish the impact of our balance exercise. Further research is, however, necessary to determine the effect of these treatment modalities on neuromuscular control, biomechanics and postural control.

Considerations for future research

'We can't prevent what we don't understand'

McLean S.G.

About two decades ago, Van Mechelen et al. proposed a prevention model for sports injuries (fig.1).⁸² This model describes 4 necessary steps to be able to develop efficient preventative measures for a specific problem. This model could be applied to the mechanism of CAI, however, as proposed here in a more curative approach. Step 1 would be establishing the key criteria assigned to define CAI, which has been done recently by the International Ankle Consortium³³. They outline repetitive ankle sprains, episode of giving way, feelings of instability and self-reported disability as key criteria for CAI. Step 2 would then be to determine the mechanisms associated with CAI, which we tried to address within our first aim. Step 3 is to use this knowledge to develop specific treatment modalities. Finally, step 4 would be to evaluate the effect of these treatment modalities on step 1, i.e. repetitive ankle sprains, episode of giving way, feelings of instability and self-reported disability. As aforementioned step 1 has been addressed, therefore we further consider step 2 to 4.



Figuur 1. Injury prevention model (adapted from van Mechelen W, Hlobil H, Kemper HC. Incidence, severity, aetiology and prevention of sports injuries. A review of concepts. Sports Med 1992;14(2):82-99)

Extensive research has been conducted in literature focusing on several potential contributors to the mechanism of CAI (step 2) but without a clear consensus, as described in the introduction of this dissertation. We focused in this dissertation on biomechanical mechanisms. As mentioned before, findings are believed to vary depending on landing task. An easy task might not require complex neuromuscular control and might therefore not be discriminative between subjects with CAI and healthy controls⁵². As we indicated in chapter 1, it might be necessary to place the system into a state in which it is more challenged, i.e. a near episode of giving way, to really elucidate kinematic alterations associated with CAI. Inducing unanticipated events might be necessary to further understand the mechanism of CAI. Lateral inflight perturbations during a jump landing protocol have been described to lead to abnormal GRF and angular motions and joint moments of the lower extremity in healthy subjects⁹⁴. Similar perturbations might aid to elucidate differences in lower limb kinematics in subjects with CAI. Another possibility might be to induce fatigue to clarify more clearly kinematic alterations associated with CAI. Fatigue has been associated with decreased neuromuscular control which may result in altered movement strategies¹⁶ and changes in the ability to absorb impact forces⁶⁹. In addition to looking for eliciting events, other analysis techniques can be considered. For instance principal component analysis has shown its applicability in identifying coordination patterns⁴⁸. Furthermore, recent technologic developments as dynamic 3D scanning might increase insight in potentially associated intrinsic foot kinematics⁸⁰.

Several intervention modalities (step 3) have been described such as mobilization, balance training, strength training, functional activities, external support^{28, 45}. These interventions are based

on mechanisms associated with CAI identified in step 2, which is common sense. However to date, developing a good rehabilitation program remains a great challenge for clinicians. As for now, the intervention studies on CAI are mainly focused on altering these mechanisms identified in step 2, as we did within our second aim. In literature, mobilization techniques have shown their effect on range of motion⁸⁴, postural control¹⁸ and landing kinematics²² in subjects with CAI; balance training leads to supraspinal adaptations⁷⁶ and some studies have shown its effect on postural control³¹; etc. Based on these intervention studies, treatment modalities are being proposed²⁸. However, to really evaluate treatment impact, step 4 in CAI research seems to be omitted. Although some studies do evaluate feelings of instability and self-reported disability following their intervention, as we did, there is a lack of research which evaluates the effect on the two key characteristics, i.e. recurrent ankle sprains and episodes of giving way. This is an important step in evaluating treatment effect. Therefore future research should focus on long term follow-up and document the key characteristics (recurrent ankle sprain, episodes of giving way, feelings of instability and self-reported instability) defined in step 1 to be able to pass judgment on the effectiveness of a treatment protocol in subjects with CAI. The ultimate goal should aim at preventing the development of CAI after the initial ankle sprain, and of course prevention of the initial sprain itself, in concordance with the injury prevention model of van Mechelen.

Clinical considerations

Chronic ankle instability (CAI) is a frequently observed residual condition, following an initial ankle sprain. Subjects with CAI complain of symptoms as pain, swelling, weakness, subjective instability and decreased levels of sport participation^{1, 49, 79}. Our study results show that subjects with CAI display task specific deviating functional movement patterns and an impaired dynamic postural control. In addition, the mechanism of CAI has been associated with other types of deficits such as impaired proprioception⁵⁰, neuromuscular control²⁴, strength⁹¹, and a decreased range of motion²⁶. Clinicians should be aware of these deficits and assess them for each individual patient as CAI is believed to be multifactorial and may vary in clinical presentation between patients.

A clinical assessment of balance, strength and range of motion is important in the clinical examination²⁸, but this was not the focus of the current dissertation. In our research, we assessed the functional movement pattern of subjects with CAI and identified task specific adaptations compared to controls. This is important to consider as a clinician when examining an individual patient. The specific problematic functional movements may vary between patients, as some

patients might experience these complaints during normal gait whilst others only during sport specific tasks. Therefore, clinicians should try to detect these patient specific tasks during intake and try to identify potentially deviating movement patterns while examining the patient. If not, treatment will lack focus. Treatment should aim at restoring these deviating movement patterns. Therefore, these tasks should be broken up into specific task related parts for rehabilitation. For example, when subjects display a stiffer landing strategy, rehabilitation could start with a step down exercise with control of foot position at touch down and lower impact on the ankle joint. Feedback can be provided verbally or visually by means of a mirror. Consequently, these exercises should gradually progress in difficulty level, which is also typically done in balance training.

When designing a balance training program, there are several ways of inducing progression in difficulty level. Classical modalities are progressing from double-legged to single-legged exercises, from static to dynamic, from a firm surface to an unstable surface, from with visual control to without, from slow to fast execution, from with feedback to without feedback (verbally and tactically, use of mirror, distractions). These progression modalities are all well-known to clinicians. However, these progression modalities have a general, non-specific character. In the appraisal of uni-axial versus multidirectional unstable devices, our research shows that a uni-axial balance board can be used to focus on specific muscles and to control the agonist-antagonist co-activation based on the foot orientation. When considering a pathology as CAI, several associated neuromuscular deficits have been described. Based on absolute muscle activity and the muscle activity ratio between the TA and PL (TA/PL ratio), we can suggest on how to gradually progress in difficulty level when rehabilitating subjects with CAI. To start, single leg stance on a firm surface evokes low muscle activity levels and also shows a low TA/PL ratio. Subsequently, training on a Airex pad evokes more activity in the PL with still a low TA/PL ratio. To maximally focus on the PL with a low TA/PL ratio, a uni-axial balance board can be used with foot oriented parallel to the axis. These exercises should be considered before introducing more provocative multi-directional devices as the BOSU, which generates high muscle activity levels of the PL, but also a higher TA/PL ratio. This gradual structure might aid to address the neuromuscular imbalance before progressing to more specific functional exercise. Therefore, the main message on balance training is to start at the base with simple specifically focused exercises before introducing the functional task specific training such as landing tasks.

Our study results demonstrated that also intrinsic segments of the foot may play a role in the mechanism of CAI. We found a more inverted medial forefoot in subjects with CAI during gait possibly related to the PL function. How to address the PL muscle during balance training has been described in the previous paragraph. Additionally, strength training of the PL should be implemented if deficits are present. These treatment modalities might restore PL function and subsequently

medial forefoot kinematics. Furthermore, the use of orthoses could be considered as foot orthoses have been shown to affect lower extremity kinematics, e.g. reducing ankle inversion moment⁴¹ and influencing midfoot kinematics²⁰, and to increase PL activity levels.²

More proximal joints should never be omitted in the assessment and treatment of CAI. Although there are no clear generic findings regarding to CAI considering hip and knee joint kinematics, strength and neuromuscular control, these more proximal factors should be evaluated on an individual basis for each patient. If deficits are observed during specific tasks, they should also be addressed in the treatment scheme.

In conclusion, CAI is a pathology with a multifactorial underlying mechanism. Clinicians should tailor their treatment to clinical findings such as strength, ROM, neuromuscular control, postural control and task specific functional movement patterns on an individual basis. When considering balance training, several principles regarding on uni-axial and multidirectional surface types should be born in mind. Furthermore, potential non-local contributing factors should not be neglected as they may very well play a role in the mechanism of CAI.

References

- (1) Anandacoomarasamy A, Barnsley L. Long term outcomes of inversion ankle injuries. *Br J Sports Med* 2005;39(3):e14.
- (2) Baur H, Hirschmuller A, Muller S, Mayer F. Neuromuscular activity of the peroneal muscle after foot orthoses therapy in runners. *Med Sci Sports Exerc* 2011;43(8):1500-1506.
- (3) Bellew JW, Frilot CF, Busch SC, Lamothe TV, Ozane CJ. Facilitating activation of the peroneus longus: electromyographic analysis of exercises consistent with biomechanical function. *J Strength Cond Res* 2010;24(2):442-446.
- (4) Blackburn JT, Hirth CJ, Guskiewicz KM. Exercise Sandals Increase Lower Extremity Electromyographic Activity During Functional Activities. *J Athl Train* 2003;38(3):198-203.
- (5) Blackwood CB, Yuen TJ, Sangeorzan BJ, Ledoux WR. The midtarsal joint locking mechanism. *Foot Ankle Int* 2005;26(12):1074-1080.
- (6) Borreani S, Calatayud J, Martin J, Colado JC, Tella V, Behm D. Exercise intensity progression for exercises performed on unstable and stable platforms based on ankle muscle activation. *Gait Posture* 2014;39(1):404-409.
- (7) Brown C, Padua D, Marshall SW, Guskiewicz K. Individuals with mechanical ankle instability exhibit different motion patterns than those with functional ankle instability and ankle sprain copers. *Clin Biomech (Bristol , Avon)* 2008;23(6):822-831.
- (8) Brown CN, Mynark R. Balance deficits in recreational athletes with chronic ankle instability. *J Athl Train* 2007;42(3):367-373.
- (9) Brown CN, Padua DA, Marshall SW, Guskiewicz KM. Variability of motion in individuals with mechanical or functional ankle instability during a stop jump maneuver. *Clin Biomech (Bristol , Avon)* 2009;24(9):762-768.
- (10) Butler RJ, Willson JD, Fowler D, Queen RM. Gender differences in landing mechanics vary depending on the type of landing. *Clin J Sport Med* 2013;23(1):52-57.
- (11) Caulfield B, Garrett M. Changes in ground reaction force during jump landing in subjects with functional instability of the ankle joint. *Clin Biomech (Bristol , Avon)* 2004;19(6):617-621.
- (12) Caulfield BM, Garrett M. Functional instability of the ankle: differences in patterns of ankle and knee movement prior to and post landing in a single leg jump. *Int J Sports Med* 2002;23(1):64-68.
- (13) Chinn L, Dicharry J, Hertel J. Ankle kinematics of individuals with chronic ankle instability while walking and jogging on a treadmill in shoes. *Phys Ther Sport* 2013.
- (14) Chuter VH, Janse de Jonge XA. Proximal and distal contributions to lower extremity injury: a review of the literature. *Gait Posture* 2012;36(1):7-15.
- (15) Cordova M, Jutte L, Hopkins J. EMG comparison of selected ankle rehabilitation exercises. *J Sport Rehab* 1999;8:209-218.
- (16) Coventry E, O'Connor KM, Hart BA, Earl JE, Ebersole KT. The effect of lower extremity fatigue on shock attenuation during single-leg landing. *Clin Biomech (Bristol , Avon)* 2006;21(10):1090-1097.
- (17) Cruz A, Bell D, McGrath M, Blackburn T, Padua D, Herman D. The effects of three jump landing tasks on kinetic and kinematic measures: implications for ACL injury research. *Res Sports Med* 2013;21(4):330-342.

- (18) Cruz-Diaz D, Lomas VR, Osuna-Perez MC, Hita-Contreras F, Martinez-Amat A. Effects of joint mobilization on chronic ankle instability: a randomized controlled trial. *Disabil Rehabil* 2014;1-10.
- (19) David P, Halimi M, Mora I, Doutrelot PL, Petitjean M. Isokinetic Testing of Evertor and Invertor Muscles in Patients with Chronic Ankle Instability. *J Appl Biomech* 2013.
- (20) Dedieu P, Drigeard C, Gjini L, Dal MF, Zanone PG. Effects of foot orthoses on the temporal pattern of muscular activity during walking. *Clin Biomech (Bristol , Avon)* 2013;28(7):820-824.
- (21) Delahunt E, Coughlan GF, Caulfield B, Nightingale EJ, Lin CW, Hiller CE. Inclusion criteria when investigating insufficiencies in chronic ankle instability. *Med Sci Sports Exerc* 2010;42(11):2106-2121.
- (22) Delahunt E, Cusack K, Wilson L, Doherty C. Joint mobilization acutely improves landing kinematics in chronic ankle instability. *Med Sci Sports Exerc* 2013;45(3):514-519.
- (23) Delahunt E, Monaghan K, Caulfield B. Altered neuromuscular control and ankle joint kinematics during walking in subjects with functional instability of the ankle joint. *Am J Sports Med* 2006;34(12):1970-1976.
- (24) Delahunt E, Monaghan K, Caulfield B. Changes in lower limb kinematics, kinetics, and muscle activity in subjects with functional instability of the ankle joint during a single leg drop jump. *J Orthop Res* 2006;24(10):1991-2000.
- (25) Delahunt E, Monaghan K, Caulfield B. Ankle function during hopping in subjects with functional instability of the ankle joint. *Scand J Med Sci Sports* 2007;17(6):641-648.
- (26) Denegar CR, Hertel J, Fonseca J. The effect of lateral ankle sprain on dorsiflexion range of motion, posterior talar glide, and joint laxity. *J Orthop Sports Phys Ther* 2002;32(4):166-173.
- (27) Denyer JR, Hewitt NL, Mitchell AC. Foot structure and muscle reaction time to a simulated ankle sprain. *J Athl Train* 2013;48(3):326-330.
- (28) Donovan L, Hertel J. A new paradigm for rehabilitation of patients with chronic ankle instability. *Phys Sportsmed* 2012;40(4):41-51.
- (29) Drewes LK, McKeon PO, Paolini G et al. Altered ankle kinematics and shank-rear-foot coupling in those with chronic ankle instability. *J Sport Rehabil* 2009;18(3):375-388.
- (30) Fong DT, Hong Y, Chan LK, Yung PS, Chan KM. A systematic review on ankle injury and ankle sprain in sports. *Sports Med* 2007;37(1):73-94.
- (31) Gauffin H, Tropp H, Odenrick P. Effect of ankle disk training on postural control in patients with functional instability of the ankle joint. *Int J Sports Med* 1988;9(2):141-144.
- (32) Gehring D, Wissler S, Mornieux G, Gollhofer A. How to sprain your ankle - a biomechanical case report of an inversion trauma. *J Biomech* 2013;46(1):175-178.
- (33) Gribble PA, Delahunt E, Bleakley C et al. Selection criteria for patients with chronic ankle instability in controlled research: a position statement of the international ankle consortium. *J Orthop Sports Phys Ther* 2013;43(8):585-591.
- (34) Gutierrez GM, Knight CA, Swanik CB et al. Examining neuromuscular control during landings on a supinating platform in persons with and without ankle instability. *Am J Sports Med* 2012;40(1):193-201.
- (35) Hass CJ, Bishop MD, Doidge D, Wikstrom EA. Chronic ankle instability alters central organization of movement. *Am J Sports Med* 2010;38(4):829-834.
- (36) Hausdorff JM, Rios DA, Edelberg HK. Gait variability and fall risk in community-living older adults: a 1-year prospective study. *Arch Phys Med Rehabil* 2001;82(8):1050-1056.

- (37) Herb CC, Chinn L, Dicharry J, McKeon PO, Hart JM, Hertel J. Shank-Rearfoot Joint Coupling With Chronic Ankle Instability. *J Appl Biomech* 2013.
- (38) Hertel J. Functional Anatomy, Pathomechanics, and Pathophysiology of Lateral Ankle Instability. *J Athl Train* 2002;37(4):364-375.
- (39) Hertel J. Sensorimotor deficits with ankle sprains and chronic ankle instability. *Clin Sports Med* 2008;27(3):353-70, vii.
- (40) Hiller CE, Kilbreath SL, Refshauge KM. Chronic ankle instability: evolution of the model. *J Athl Train* 2011;46(2):133-141.
- (41) Hsu WH, Lewis CL, Monaghan GM, Saltzman E, Hamill J, Holt KG. Orthoses posted in both the forefoot and rearfoot reduce moments and angular impulses on lower extremity joints during walking. *J Biomech* 2014;47(11):2618-2625.
- (42) Hunt AE, Smith RM, Torode M. Extrinsic muscle activity, foot motion and ankle joint moments during the stance phase of walking. *Foot Ankle Int* 2001;22(1):31-41.
- (43) Hupperets MD, Verhagen EA, van Mechelen W. The 2BFit study: is an unsupervised proprioceptive balance board training programme, given in addition to usual care, effective in preventing ankle sprain recurrences? Design of a randomized controlled trial. *BMC Musculoskelet Disord* 2008;9:71.
- (44) Kaltenborn F. Mobilization of the extremity joints. 3rd ed. Olaf Norlis Bokhandel; 1980.
- (45) Kaminski TW, Hertel J, Amendola N et al. National athletic trainers' association position statement: conservative management and prevention of ankle sprains in athletes. *J Athl Train* 2013;48(4):528-545.
- (46) Kavanagh JJ, Bisset LM, Tsao H. Deficits in reaction time due to increased motor time of peroneus longus in people with chronic ankle instability. *J Biomech* 2012;45(3):605-608.
- (47) Kipp K, Palmieri-Smith RM. Principal component based analysis of biomechanical inter-trial variability in individuals with chronic ankle instability. *Clin Biomech (Bristol , Avon)* 2012;27(7):706-710.
- (48) Kipp K, Palmieri-Smith RM. Differences in kinematic control of ankle joint motions in people with chronic ankle instability. *Clin Biomech (Bristol , Avon)* 2013.
- (49) Konradsen L, Bech L, Ehrenbjerg M, Nickelsen T. Seven years follow-up after ankle inversion trauma. *Scand J Med Sci Sports* 2002;12(3):129-135.
- (50) Konradsen L, Magnusson P. Increased inversion angle replication error in functional ankle instability. *Knee Surg Sports Traumatol Arthrosc* 2000;8(4):246-251.
- (51) Konradsen L, Ravn JB. Prolonged peroneal reaction time in ankle instability. *Int J Sports Med* 1991;12(3):290-292.
- (52) Koshino Y, Yamanaka M, Ezawa Y et al. Lower limb joint motion during a cross cutting movement differs in individuals with and without chronic ankle instability. *Phys Ther Sport* 2013.
- (53) Lin CF, Chen CY, Lin CW. Dynamic ankle control in athletes with ankle instability during sports maneuvers. *Am J Sports Med* 2011;39(9):2007-2015.
- (54) Liu K, Glutting J, Wikstrom E, Gustavsen G, Royer T, Kaminski TW. Examining the diagnostic accuracy of dynamic postural stability measures in differentiating among ankle instability status. *Clin Biomech (Bristol , Avon)* 2013;28(2):211-217.
- (55) Mattacola CG, Dwyer MK. Rehabilitation of the Ankle After Acute Sprain or Chronic Instability. *J Athl Train* 2002;37(4):413-429.

- (56) McLoda TA, Hansen AJ, Birrer DA. EMG analysis of peroneal and tibialis anterior muscle activity prior to foot contact during functional activities. *Electromyogr Clin Neurophysiol* 2004;44(4):223-227.
- (57) Mickel TJ, Bottoni CR, Tsuji G, Chang K, Baum L, Tokushige KA. Prophylactic bracing versus taping for the prevention of ankle sprains in high school athletes: a prospective, randomized trial. *J Foot Ankle Surg* 2006;45(6):360-365.
- (58) Monaghan K, Delahunt E, Caulfield B. Ankle function during gait in patients with chronic ankle instability compared to controls. *Clin Biomech (Bristol, Avon)* 2006;21(2):168-174.
- (59) Monteleone BJ, Ronsky JL, Meeuwisse WH, Zernicke RF. Ankle Kinematics and Muscle Activity in Functional Ankle Instability. *Clin J Sport Med* 2013.
- (60) Morrison KE, Kaminski TW. Foot characteristics in association with inversion ankle injury. *J Athl Train* 2007;42(1):135-142.
- (61) Muehlbauer T, Roth R, Bopp M, Granacher U. An exercise sequence for progression in balance training. *J Strength Cond Res* 2012;26(2):568-574.
- (62) Olmsted LC, Vela LI, Denegar CR, Hertel J. Prophylactic Ankle Taping and Bracing: A Numbers-Needed-to-Treat and Cost-Benefit Analysis. *J Athl Train* 2004;39(1):95-100.
- (63) Pataky TC. Generalized n-dimensional biomechanical field analysis using statistical parametric mapping. *J Biomech* 2010;43(10):1976-1982.
- (64) Pataky TC, Robinson MA, Vanrenterghem J. Vector field statistical analysis of kinematic and force trajectories. *J Biomech* 2013;46(14):2394-2401.
- (65) Perez HR, Reber LK, Christensen JC. The effect of frontal plane position on first ray motion: forefoot locking mechanism. *Foot Ankle Int* 2008;29(1):72-76.
- (66) Phillips LH. Sports injury incidence. *Br J Sports Med* 2000;34(2):133-136.
- (67) Pintsaar A, Brynhildsen J, Tropp H. Postural corrections after standardised perturbations of single limb stance: effect of training and orthotic devices in patients with ankle instability. *Br J Sports Med* 1996;30(2):151-155.
- (68) Pourkazemi F, Hiller CE, Raymond J, Nightingale EJ, Refshauge KM. Predictors of chronic ankle instability after an index lateral ankle sprain: A systematic review. *J Sci Med Sport* 2014.
- (69) Santamaria LJ, Webster KE. The effect of fatigue on lower-limb biomechanics during single-limb landings: a systematic review. *J Orthop Sports Phys Ther* 2010;40(8):464-473.
- (70) Santilli V, Frascarelli MA, Paoloni M et al. Peroneus longus muscle activation pattern during gait cycle in athletes affected by functional ankle instability: a surface electromyographic study. *Am J Sports Med* 2005;33(8):1183-1187.
- (71) Sawkins K, Refshauge K, Kilbreath S, Raymond J. The placebo effect of ankle taping in ankle instability. *Med Sci Sports Exerc* 2007;39(5):781-787.
- (72) Schubert M, Beck S, Taube W, Amtage F, Faist M, Gruber M. Balance training and ballistic strength training are associated with task-specific corticospinal adaptations. *Eur J Neurosci* 2008;27(8):2007-2018.
- (73) Shultz SJ, Schmitz RJ, Tritsch AJ, Montgomery MM. Methodological considerations of task and shoe wear on joint energetics during landing. *J Electromyogr Kinesiol* 2012;22(1):124-130.
- (74) Suda EY, Amorim CF, Sacco IC. Influence of ankle functional instability on the ankle electromyography during landing after volleyball blocking. *J Electromyogr Kinesiol* 2009;19(2):e84-e93.

- (75) Suda EY, Sacco IC. Altered leg muscle activity in volleyball players with functional ankle instability during a sideward lateral cutting movement. *Phys Ther Sport* 2011;12(4):164-170.
- (76) Taube W, Gruber M, Gollhofer A. Spinal and supraspinal adaptations associated with balance training and their functional relevance. *Acta Physiol (Oxf)* 2008;193(2):101-116.
- (77) Terada M, Pietrosimone BG, Gribble PA. Alterations in Neuromuscular Control at the Knee in Individuals With Chronic Ankle Instability. *J Athl Train* 2014.
- (78) van der Wees PJ, Lenssen AF, Hendriks EJ, Stomp DJ, Dekker J, de Bie RA. Effectiveness of exercise therapy and manual mobilisation in ankle sprain and functional instability: a systematic review. *Aust J Physiother* 2006;52(1):27-37.
- (79) van Rijn RM, van Os AG, Bernsen RM, Luijsterburg PA, Koes BW, Bierma-Zeinstra SM. What is the clinical course of acute ankle sprains? A systematic literature review. *Am J Med* 2008;121(4):324-331.
- (80) Van den Herrewegen I, Cuppens K, Broeckx M et al. Dynamic 3D scanning as a markerless method to calculate multi-segment foot kinematics during stance phase: Methodology and first application. *J Biomech* 2014;47(11):2531-2539.
- (81) Van Deun S, Staes FF, Stappaerts KH, Janssens L, Levin O, Peers KK. Relationship of chronic ankle instability to muscle activation patterns during the transition from double-leg to single-leg stance. *Am J Sports Med* 2007;35(2):274-281.
- (82) van Mechelen W, Hlobil H, Kemper HC. Incidence, severity, aetiology and prevention of sports injuries. A review of concepts. *Sports Med* 1992;14(2):82-99.
- (83) Verhagen E, van der Beek A, Twisk J, Bouter L, Bahr R, van Mechelen W. The effect of a proprioceptive balance board training program for the prevention of ankle sprains: a prospective controlled trial. *Am J Sports Med* 2004;32(6):1385-1393.
- (84) Vicenzino B, Branjerdporn M, Teys P, Jordan K. Initial changes in posterior talar glide and dorsiflexion of the ankle after mobilization with movement in individuals with recurrent ankle sprain. *J Orthop Sports Phys Ther* 2006;36(7):464-471.
- (85) Wahl MJ, Behm DG. Not all instability training devices enhance muscle activation in highly resistance-trained individuals. *J Strength Cond Res* 2008;22(4):1360-1370.
- (86) Webster KA, Gribble PA. Functional rehabilitation interventions for chronic ankle instability: a systematic review. *J Sport Rehabil* 2010;19(1):98-114.
- (87) Webster KA, Gribble PA. A comparison of electromyography of gluteus medius and maximus in subjects with and without chronic ankle instability during two functional exercises. *Phys Ther Sport* 2013;14(1):17-22.
- (88) Wikstrom EA, Brown CN. Minimum reporting standards for copers in chronic ankle instability research. *Sports Med* 2014;44(2):251-268.
- (89) Wikstrom EA, Tillman MD, Chmielewski TL, Cauraugh JH, Naugle KE, Borsa PA. Discriminating between copers and people with chronic ankle instability. *J Athl Train* 2012;47(2):136-142.
- (90) Willems T, Witvrouw E, Delbaere K, De CA, De Clercq D. Relationship between gait biomechanics and inversion sprains: a prospective study of risk factors. *Gait Posture* 2005;21(4):379-387.
- (91) Willems T, Witvrouw E, Verstuyft J, Vaes P, De Clercq D. Proprioception and Muscle Strength in Subjects With a History of Ankle Sprains and Chronic Instability. *J Athl Train* 2002;37(4):487-493.

- (92) Willems TM, Witvrouw E, Delbaere K, Philippaerts R, De Bourdeaudhuij I, De Clercq D. Intrinsic risk factors for inversion ankle sprains in females--a prospective study. *Scand J Med Sci Sports* 2005;15(5):336-345.
- (93) Wright IC, Neptune RR, van den Bogert AJ, Nigg BM. The influence of foot positioning on ankle sprains. *J Biomech* 2000;33(5):513-519.
- (94) Yom JP, Simpson KJ, Arnett SW, Brown CN. The Effects of a Lateral In-flight Perturbation on Lower Extremity Biomechanics During Drop Landings. *J Appl Biomech* 2014.

Summary

An ankle sprain is one of the most common sport related injuries. In many cases, this ankle sprain is considered your everyday injury which is easily treated with a good outcome. However, follow-up studies indicate the contrary. Many patients suffer from residual symptoms such as pain, swelling, weakness, 'giving way' and subjective instability, lower activity levels or they even change to other sports. These residual symptoms have been termed chronic ankle instability (CAI). Literature shows that the mechanism of CAI is associated with various types of deficits such as impaired proprioception, neuromuscular control, postural control and strength, a decreased range of motion and deviating functional movement patterns. As a consequence of the fact that CAI has a multifactorial foundation, rehabilitation should address the various deficits present in patients with CAI. Conventional treatment modalities are mostly focused at restoring ROM, increasing strength, restoring neuromuscular control and postural control.

The first aim of this dissertation was to **explore biomechanical mechanisms associated with CAI**. Furthering insight in potentially altered motion patterns of subjects with CAI may identify those deflections which could be associated with an ankle sprain event or an episode of 'giving way'. Furthermore, exploring multi-segmented foot kinematics may be beneficial in understanding foot mechanisms associated with CAI. Results of our studies demonstrated both local contributors related to the ankle joint and non-local contributors related to the foot complex have been found. Subjects with CAI displayed a stiffer landing pattern at the ankle joint associated with higher loading rates during a vertical drop, potentially increasing susceptibility to injury. However, this finding was not generic for all included landing tasks, emphasizing the observed results to be task specific. During both walking and running, an increased inverted position of the medial forefoot (first ray) was found during the mid- and late stance phase. This inverted position could be associated with an impaired function of the m. peroneus longus (PL) during gait in subjects with CAI. This may result in a so-called loose-packed position of the medial forefoot which reflects a mechanically less stable condition. Furthermore, subjects with CAI also displayed a more inverted position of the midfoot throughout the whole impact phase of the side jump compared to controls. As the midfoot fulfills an important role in coupling rearfoot and forefoot motion, further research might elucidate the impact of midfoot kinematics observed in the current study by investigating the forefoot and rearfoot coupling in CAI. Our results do not confirm the involvement

of more proximal non-local joint kinematics in the mechanism of CAI. However, solely based on our study, and in view of described neuromuscular, kinematic and task specific adaptations, we cannot definitively rule out hip and knee joint contribution in a generic context.

The treatment of CAI remains quite a challenge for clinicians since the underlying multifactorial mechanism of CAI is still as of yet unclear and the evidence for possible treatment modalities are limited. The second aim of this dissertation was to **evaluate the effect of treatment modalities on postural control in subjects with CAI**. It is believed that a more stable body results in a reduced incidence of recurrent lower extremity injuries emphasizing that improving postural control is an important aspect of injury prevention. In general, our study results did not demonstrate an improvement in dynamic postural control following our balance training and taping protocol. Regarding the balance training, a possible explanation might be found in the specificity of the balance training program used in our study as it remains unclear which exercises best serve the rehabilitation purposes. The taping procedure on the other hand, did show to be effective in altering foot positioning at landing and limiting ROM during impact. The lack of effect of tape on postural control might be explained by the limited possibility to use an efficient 'ankle strategy' to maintain balance by performing pro- and supination motions. Subjects might therefore be compelled to use a less efficient 'hip strategy', potentially leading to higher shear forces. Both treatment modalities did show their capacity of improving subjective feelings of stability which can be considered an important treatment effect as this may affect the effectiveness of the treatment modality.

The main goal of balance training is regaining a normal neuromuscular control around the ankle to a functional level. However, it remains as of yet unclear which exercises included in a balance training protocol best serve the rehabilitations goals. Therefore, the third aim of dissertation was **to create a rationale for developing a balance training program**. Our results showed that when performing single leg balance exercises on a uni-axial balance board, the foot orientation determined which ankle stabilizing muscle was targeted based on anatomical function. Furthermore, we found no differences in impact of the evaluated surface types on muscle activity levels of ankle stabilizing muscles between subjects with CAI and healthy controls. Based on absolute muscle activity and the muscle activity ratio between the m. tibialis anterior (TA) and PL (TA/PL ratio), we made suggestions how to gradually progress in difficulty level when rehabilitating subjects with CAI. A uni-axial balance board should be used to control the agonist-antagonist co-activation based on the foot orientation. Consequently, to maximally focus on the PL in subjects

with CAI with a low TA/PL ratio, exercising on a uni-axial balance board with the foot parallel to the axis has been proven the best choice. A gradual progression might aid to address the neuromuscular imbalance before progressing to more specific functional exercise.

Nederlandse samenvatting

Een enkelverstuiking is een van de meest voorkomende sportblessures. Meestal wordt een enkelverstuiking beschouwd als een alledaags letsel dat gemakkelijk te behandelen is met een goede prognose. Follow-up studies geven echter het tegendeel aan. Veel patiënten rapporteren restklachten zoals pijn, zwelling, zwakte, 'giving way' en subjectieve instabiliteit, lager activiteitsniveau of ze veranderen zelfs van sport. Deze restklachten worden samengebracht onder de algemene term chronische enkelinstabiliteit (CEI). De literatuur toont aan dat het onderliggende mechanisme van CEI geassocieerd is met verschillende factoren, zoals verminderde proprioceptie, neuromusculaire controle, posturale controle, kracht, bewegingsuitslag en afwijkende functionele bewegingspatronen. Vermits CEI een multifactoriële achtergrond heeft, moet de revalidatie dan ook gericht zijn op de verschillende aanwezige factoren bij patiënten met CEI. Conventionele behandelingen zijn vooral gericht op het herstellen van de bewegingsuitslag, het verbeteren van kracht en het herstel van de neuromusculaire en posturale controle.

Het eerste doel van dit doctoraat was om **mogelijke biomechanische mechanismen geassocieerd met CEI verder te verkennen**. Het vergroten van het inzicht in mogelijk veranderde bewegingspatronen bij personen met CEI kan helpen om die adaptaties te identificeren die zouden kunnen leiden tot een enkelverstuiking of een episode van 'giving way'. Daarnaast kan het gebruik van een voetmodel bestaande uit meerdere segmenten een meerwaarde betekenen om de rol van voetmechanisme binnen het gegeven CEI beter te begrijpen. In onze studies werden zowel lokale factoren aangetoond ter hoogte van het enkelgewricht als niet-lokale factoren ter hoogte van het voetcomplex. Personen met CEI vertoonden een stijver landingspatroon ter hoogte van het enkelgewricht geassocieerd met een hogere belastingssnelheid tijdens een verticale drop landing. Dit zou de kans op het oplopen van een letsel kunnen vergroten. Deze bevindingen kan men echter niet algemeen doorgetrekken naar andere functionele landingstaken, hetgeen wijst op een eerder taakspecifiek karakter van de bevindingen dan op een generiek patroon. Zowel tijdens wandelen als lopen werd een grotere geïnverteerde positie van de mediale voorvoet (eerste straal) gevonden gedurende het midden en einde van de standfase. Deze geïnverteerde positie kan worden geassocieerd met een verminderde functie van de m. peroneus longus (PL) bij patiënten met CEI. Dit kan resulteren in een zogenaamde loose-packed positie van de mediale voorvoet hetgeen een mechanisch minder stabiele toestand betekent. Daarnaast vertonen

patiënten met CEI ook een meer geïnverteerde positie van de middenvoet tijdens een zijwaartse spronglanding in vergelijking met een controlegroep. Aangezien de middenvoet een belangrijke rol vervult bij het koppelen van achtervoet en voorvoet bewegingen, zou verder onderzoek naar middenvoet kinematica de mogelijke impact ervan op deze koppeling bij personen met CEI kunnen verhelderen. Onze resultaten tonen geen betrokkenheid aan van meer proximale niet-lokale gewrichtskinematica in het mechanisme van de CEI. Gezien de beschreven neuromusculaire, kinematische en taakspecifieke aanpassingen, kunnen we enkel op basis van onze resultaten niet definitief uitsluiten dat het heup- en kniegewricht mogelijks bijdragen tot het onderliggende mechanisme van CEI.

De behandeling van CEI blijft een moeilijke uitdaging voor klinici omdat het onderliggende multifactoriële mechanisme nog steeds onduidelijk is en de evidentie voor de mogelijke behandelingsstrategieën beperkt is. Het tweede doel van dit proefschrift was **om het effect van verschillende behandelingsmodaliteiten op de posturale controle te evalueren bij personen met CEI**. Een stabiel lichaam zou een verminderde incidentie van recidiverende letsels ter hoogte van de onderste ledematen tot gevolg hebben. Dit benadrukt nogmaals het belang van een optimale posturale controle binnen letselpreventie. In het algemeen, hebben we in onze studies geen verbetering van de dynamische posturale controle kunnen aantonen na balanstraining en na taping bij personen met CEI. Met betrekking tot de balanstraining kan een mogelijke verklaring te vinden zijn in de specificiteit van het trainingsprogramma die we gebruikt hebben in onze studie, vermits het onduidelijk blijft welke oefeningen de beste resultaten geven. De taping procedure aan de andere kant, bleek effectief in het veranderen van de voetpositie bij de landing en het beperken van bewegingsuitslag. Het zou kunnen dat de tape de mogelijkheid vermindert om een efficiënte 'enkel strategie' te gebruiken om evenwicht te bewaren door de beperking van pro-en supinatie bewegingen, waardoor we geen effect zien op posturale controle. Personen kunnen daarom gedwongen worden om een minder efficiënte 'heup strategie' te gebruiken, wat kan leiden tot hogere schuifkrachten. Beide behandelingsmodaliteiten hebben wel hun vermogen getoond om het subjectieve stabiliteitsgevoel te verbeteren wat kan beschouwd worden als een belangrijk resultaat omdat dit de effectiviteit van de behandelingsmodaliteit kan beïnvloeden.

Het belangrijkste doel van balanstraining is het herwinnen van een normale functionele neuromusculaire controle rond het enkelgewricht. Het blijft echter vooralsnog onduidelijk welke oefeningen in een balanstraining protocol best de revalidatiedoelen dienen. Daarom was het derde doel van dit doctoraat om **een rationale uit te werken voor het opstellen van een**

balanstraining. Onze resultaten tonen aan dat bij het uitvoeren van unipodale oefeningen op een uni-axiale kantelplank, de oriëntatie van de voet bepaalt welke stabiliserende spieren rond de enkel meest worden aangesproken op basis van hun anatomische functie. Verder vonden we geen verschillen in spieractiviteit van de stabiliserende spieren tussen proefpersonen met CEI en gezonde controles tijdens balanstraining op verschillende types ondergrond. Gebaseerd op absolute spieractiviteit en de ratio van de m. tibialis anterior (TA) ten opzichte van de PL (TA / PL-ratio), kunnen we een aantal suggesties doen om de moeilijkheidsgraad progressief op te bouwen bij de revalidatie van patiënten met CEI. Een uni-axiale kantelplank kan worden gebruikt om de agonist-antagonist co-activatie te beïnvloeden op basis van de oriëntatie van de voet. Om bijgevolg maximaal te focussen op de PL bij patiënten met CEI met een lage TA / PL contractie, is oefenen op een uni-axiale kantelplank met de voet parallel georiënteerd aan de as de beste keuze. Een geleidelijke opbouw kan wellicht helpen om het neuromusculaire onevenwicht aan te pakken alvorens over te gaan tot meer specifieke functionele oefeningen.

List of abbreviations

AMTI	Advanced Mechanical Technology Inc.	S	Subtalar
ABD	Abduction	TD	Touch Down
ADD	Adduction	VAS	Visual Analogue Scale
APSI	Anterior-Posterior Stability Index	VSI	Vertical Stability Index
ATFL	Anterior Talofibular Ligament	WobF	Wobble board with the foot aligned to the frontal axis
BMI	Body Mass Index		
BW	Body weight	WobD	Wobble board with the foot aligned to the diagonal axis
CAI	Chronic Ankle Instability		
CFL	Calcaneofibular Ligament		
CoM	Centre of Mass		
CON	Control		
COP	Coper		
D	Diagonal		
DPSI	Dynamic Postural Stability Index		
DF	Dorsiflexion		
EC	Eyes Closed		
EO	Eyes Open		
EV	Eversion		
F	Frontal		
FADI	Foot and Ankle Disability Index		
FADI-S	Foot and Ankle Disability Index Sports subscale		
GRF	Ground Reaction Force		
IN	Inversion		
LG	Lateral Gastrocnemius		
MaxDF	Maximal Dorsiflexion		
Mean Diff	Mean Difference		
MG	Medial Gastrocnemius		
MLSI	Medio-Lateral Stability Index		
MVC	Maximum Voluntary Contraction		
PF	Plantar flexion		
PL	Peroneus Longus		
TA	Tibialis Anterior		
ROM	Range Of Motion		
RMS	Root Mean Square		
S	Sagittal		
SEBT	Star Excursion Balance Test		
SPM	Statistical Parametric Mapping		
SPSS	Statistical Package for Social Sciences		