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TESI DI LAUREA

EFFECTS OF EXTERNAL BIOFEEDBACK INTERVENTIONS IN INDIVIDUALS WITH CHRONIC ANKLE INSTABILITY: A SCOPING REVIEW

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ABSTRACT

Clinical scenario. There is clinical evidence that about 1 in 3 acute lateral ankle sprains results in chronic ankle instability (CAI). Chronic ankle instability is a condition characterized by a history of one significant lateral ankle sprain, feelings of instability, pain, and decreased self-reported function. People with CAI show a multitude of mechanical and functional impairments, including an altered activation of the peroneus longus, a more inverted position of the foot during walking and an increased lateral plantar pressure distribution. These factors contribute to high recurrence of ankle sprains, a reduction in activities and sports participation, and an early onset of post-traumatic ankle osteoarthritis. Current rehabilitation and prevention protocols for CAI have not been successful in improving the altered biomechanics showed by this population, biofeedback interventions specifically target biomechanics impairments in those with CAI, but their effectiveness has yet to be fully clarified.

Purpose: to examine the effects of biofeedback interventions on biomechanics and muscular activation during gait and functional tasks in individuals with chronic ankle instability.

Methods. A literature revision was conducted based on the research question and the keywords were combined with the Boolean operators "AND" or "OR" to create a string to be used to search the following databases: Pubmed, PEDro, Cochrane Library and Scopus. Records were screened based on determined inclusion/exclusion criteria and quality.

Results & discussion. At the end of the selection, seven articles were included in the study. Studies have assessed biofeedback interventions using visual biofeedback (n = 3), auditory biofeedback (n = 3), haptic biofeedback (n = 2). They found biofeedback gait re-training can diminish plantar pressure in the lateral column of the foot, cause a medial shift of the center of pressure, and reduce ankle inversion at initial contact. Similar results in plantar pressure distribution have been reported also during more complex functional tasks. These modifications not only may have an important role in reducing the risk of recurrent ankle sprain, but they were also associated with significant improvements in patient-reported function which is typically impaired in people with CAI. Moreover, biofeedback strategy allow a decrease in vertical ground reaction force and ankle joint forces which are considered major factors for the development of post-traumatic ankle osteoarthritis. However, all these findings are short-term effects and thus, further studies should assess biofeedback interventions' effects in the long-term.

Conclusion the use of biofeedback in individuals with chronic ankle instability resulted in several positive effects on clinical-oriented outcomes as well as patient-reported outcomes. Therefore,

implementing external biofeedback training into a structured multi-session rehabilitation program may allow for greater improvements in impairments associated with CAI. However, future research to assess long-term effects of external biofeedback strategies in patients with CAI is needed.

SUMMARY

1. INTRODUCTION

1.1 Personal motivation and scientific interest

This thesis was born from the desire of better understanding the reasons why ankle instability is such a frequent condition among young and adult people, what are the evidence available for chronic ankle instability (CAI) rehabilitation and if there is any lack in current rehabilitation protocols.

Lateral ankle sprains are one of the most common musculoskeletal injuries and have been documented as the most prevalent lower extremity injury among physically active individuals with some estimates attributing upward of 45% of all athletic injuries to ankle sprains(1). In the USA alone, it has been estimated that over two million ankle sprains occur each year(2) placing a huge burden on health care industry. The high recurrence rate of ankle sprains and the evidence that about 40% of people who experienced a first ankle sprain develop chronic ankle instability(3) suggest that current rehabilitation procedures for ankle sprains and CAI condition should be reconsidered. In 2021 updated clinical practice guidelines for CAI rehabilitation were published by the Journal of Orthopaedic & Sports Physical Therapy(4). However, biofeedback training, which has been proven to bring benefits to those with CAI, has not be mentioned.

The adoption of external biofeedback interventions has become in the last few years so common and usual in the rehabilitation field that its effectiveness is widely accepted. However, evidence on biofeedback rehabilitation strategies is missing and, if biofeedback ability of promoting patients' recovery is limited, the mechanism underlying the modification it produces is still unclear. Therefore, the aim of this work is to study the effect of biofeedback interventions in chronic ankle instability population and investigate what is their impact on both clinically-oriented measures and patient-reported outcome measures.

1.2 Topographical and functional anatomy of the ankle

The ankle joint, also known as the talocrural joint, is the distal joint of the lower limb that connects the bones of the leg, the fibula and tibia, with the talus of the foot. As a hinged joint, the ankle joint has only one degree of freedom allowing movements of flexion-extension on the transverse axis.
Being the terminal structures of the lower limb, the ankle joint and the foot provide both mobility and stability. During monopodal support, the foot bears the entire weight of the body with minimum muscle energy expenditure and absorb the ground reaction force applied by the ground to the foot which transmit this force through the ankle joint to the proximal structures of the limb. The foot must also be both pliable and relatively rigid depending on various functional demands, this versatility allows the foot to absorb forces, accommodate to uneven surfaces, or serve as a structural lever to propel the body forward during walking and running(5).

1.2.1 Tibia and fibula: the bones of the leg

The tibia bone is formed by the proximal and distal epiphysis and a triangular diaphysis. The distal extremity presents on the medial side a bone projection called medial malleolus with its articular surface, and on the lateral side the fibular incisura, where the fibula articulates with the tibia through the distal tibiofibular joint. On the lower face of the tibia there is the tibial articular surface, which participates in the talocrural joint, and posteriorly a bone projection is known as the Destot malleolus or the third malleolus of the ankle joint. The fibula is the second bone of the leg, it is as long as the tibia but is thinner and less robust than the tibia. The inferior part terminates with the lateral malleolus, which internal face presents an articular surface for the articulation with the talus.

1.2.2 Talus

The talus is composed by three parts: the head, the body and the neck of the talus.
Talus head has a convex shape and an articular surface for the navicular bone. Its inferior surface carries two of the three articular areas for the articulation with the calcaneus bone. Talus neck is the narrow region between head and body. Talus body is cuboidal in shape. Its inferior surface carries the big calcaneal articular surface while the upper surface articulates with the tibiotarsal mortar. The trochlear surface articulates with the distal end of the tibia, medially a smaller articular area articulates with the medial malleolus while on the lateral surface of the talus the lateral tuberculum carries a triangular articular surface for the articulation with the lateral malleolus.

1.2.3 Ankle joints

The ankle complex consists of three articulations: the talocrural or ankle joint, the inferior tibiofibular joint and the subtalar joint.

1.2.3.1 *Inferior tibiofibular joint*

The inferior tibiofibular joint is the articulation between the distal parts of tibia and fibula. It is reinforced by the anterior and posterior tibiofibular ligaments and by the interosseous membrane, which is a rigid and robust structure, connecting tibia and fibula bones. Injuries at the tibiofibular joint are called high ankle sprains or syndesmotic ankle sprains.

1.2.3.2 *Talocrural joint*

The talocrural joint is the articulation between the inferior surface of the tibia, the medial malleolus, and the lateral malleolus with the talus. The medial and lateral malleoli and the tibia inferior articular surface form together the ankle mortise which can be described as a notch in which the body of the talus fits. The distal end of the tibia, which has a concave shape, articulates with the convex trochlea of the talus. The medial malleolus articulates with the medial surface of the talus while the lateral malleolus articulates with the lateral aspect of the talus. Compared to the medial malleolus, the lateral malleolus of the fibula is larger in size and is positioned more distally and posteriorly. In addition, the articular surface of the lateral malleolus isn't in continuity with the articular surface of the tibia, as for the medial malleolus, but is separated from the articular surface of the tibia by the syndesmotic joint between the tibia and the fibula. The ankle joint is a synovial joint with a joint capsule that encloses the synovial liquid located in the joint cavity. The joint capsule is attached proximally to the margins of the articular surfaces of the medial malleoli, tibia, and lateral malleoli, and is attached to the margins of the trochlear surface of the talus distally. The capsule is thin and weak anteriorly and posteriorly, allowing greater range of movement, while strong ligaments reinforce it on the medial and lateral sides.

1.2.3.3 *Subtalar joint*

The subtalar joint is the articulation between the talus superiorly and the calcaneus and navicular inferiorly. It consists of two separate joint cavities. The posterior part of the subtalar joint also known as talocalcaneal joint is an articulation between the posterior calcaneal articular surface of the talus (concave) with the posterior facet of the calcaneus (convex). The anterior part of the subtalar joint is formed by the talar head which articulates with the anterior and the middle facets of the calcaneus, and by the articulation between the talus and navicular. The latter is also referred as talocalcaneonavicular joint. These joints have a common axis of motion so that they can be described as a one functional unit. The movements that occur at the subtalar joint are gliding and rotation whose combination results in inversion and eversion movements.

1.2.4 Ankle ligaments

The medial aspect of the ankle joint is strengthened by the medial collateral ligament (Fig. 1, (6)). This ligament, also called deltoid ligament, is composed by four bands. From a unique proximal attachment on the apex of the medial malleolus, the medial collateral ligament divides into four parts based on the distal attachment points:

- Tibionavicular ligament (TNL) connects the medial malleoli to the navicular bone. It is more superficial than the anterior band of the tibiotalar ligament.
- Tibiocalcaneal ligament (TCL) represents the intermediate part of the medial collateral ligament that descends almost vertically from the medial malleolus to attach onto the sustentaculum tali of the calcaneus.
- Tibiotalar ligament is further divided in two parts, the anterior tibiotalar band (ATTL) attaches onto the talus, the posterior band (PTTL) descends from the medial malleolus to the posterior prominence of the talus.

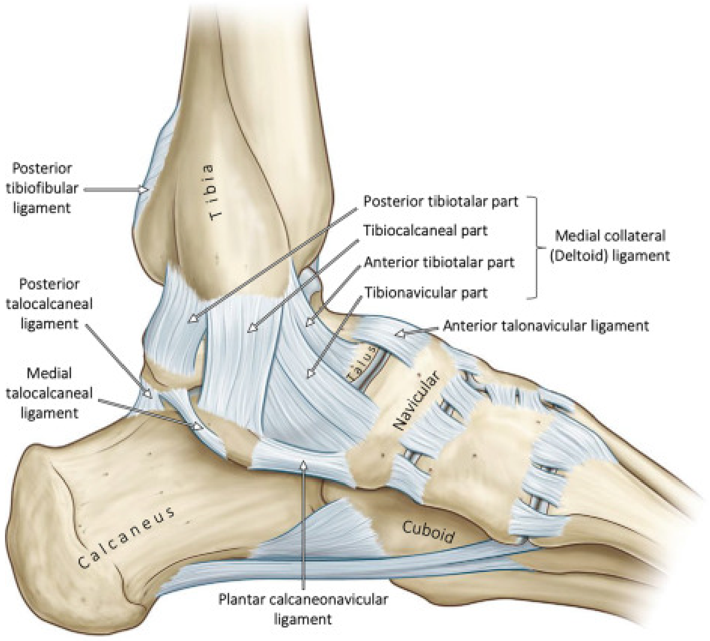


Figure 1: Medial ankle ligaments (6)

Laterally the ankle has stabilization from three separate ligaments, the anterior and posterior talofibular ligaments, and the calcaneofibular ligament (Fig. 2).

Anterior talofibular ligament (ATFL) connects the lateral malleolus with the neck of the talus. Being a thin and weak ligament is the most frequently injured.

Posterior talofibular ligament (PTFL) has an almost horizontal course from the malleolar fossa of the fibula to the lateral tubercle of the talus.

Calcaneofibular ligament (CFL) originates from the apex of the lateral malleolus of the fibula and extends posteroinferiorly to attach on a tubercle on the lateral surface of the calcaneus.

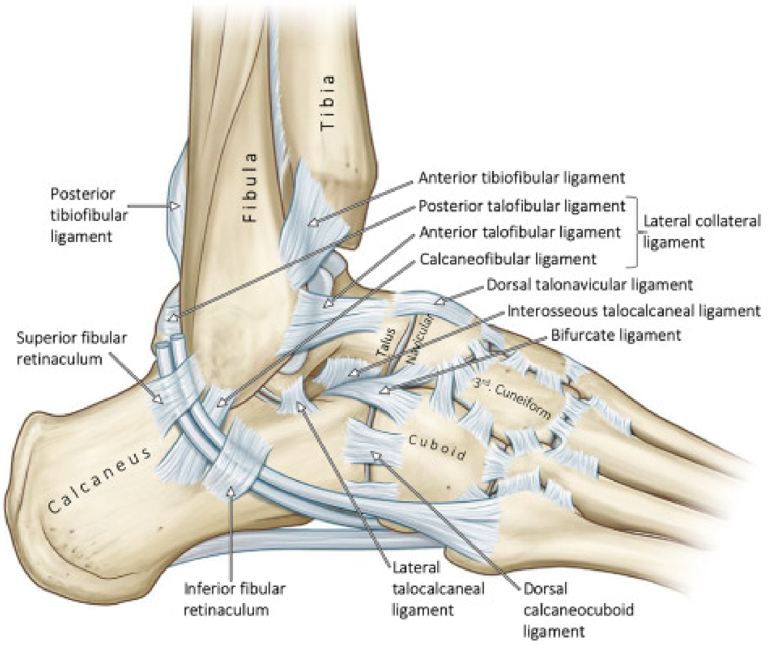


Figure 2: Lateral ankle ligaments (6)

The tibiofibular ligaments (Fig. 3) reinforce the distal tibiofibular joint.
The anterior inferior tibiofibular ligament (AITFL) connects the tibia to the fibula.
The posterior inferior tibiofibular ligament (PITFL) and the transverse ligament connects the tibia to the fibula with a transverse course.

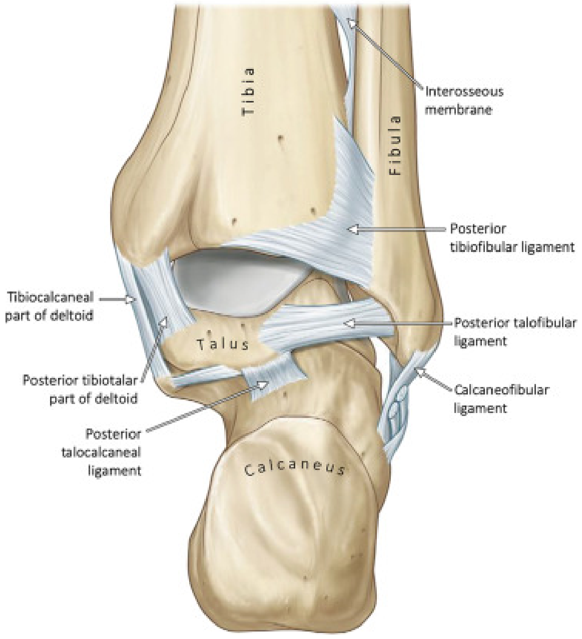


Figure 3: Tibiofibular ligaments (6)

1.2.5 Ankle functional movements

As a hinged joint, the only movement allowed by the ankle joint is a movement of flexion-extension around the transverse axis passing through malleoli (that axis does not correspond exactly to the transverse plane). When referred to the ankle movements, flexion is called dorsi-flexion and is defined as the movement that get the foot closer to the leg and reduces the angle between foot and leg. On the other hand, extension, described as plantar-flexion, is the movement that move the foot away from the leg so that the angle between the foot and leg increases. Due to the peculiar conformation of the talus, which is larger anteriorly than posteriorly, the range of motion of plantarflexion is greater than that of dorsiflexion(7). During dorsiflexion, the anterior part of the talus comes in contact with the ankle mortise and limits the range of motion to about 30°. When the foot is plantarflexed, instead, the talus isn't embedded in the ankle mortise and thus the range of motion is wider (up to 40°) and the position results more instable than dorsiflexion.

If plantar and dorsiflexion movements are mainly performed by the talocrural joint, the subtalar and talocalcaneonavicular joints perform the movements of pronation-supination and abduction-adduction. The movements of pronation and supination occur around the longitudinal axis of the foot which is in the sagittal plane. Supination is an internal rotation of the foot with a range of motion of 50°, while pronation is an external rotation of the foot with a range of 25-30°. Abduction and adduction occur around the longitudinal axis of the leg. Abduction is defined as the moving of the segment away from the midline of the body (toe out) while adduction is defined as moving toward the midline (toe in). Due to the morphological-functional characteristics of the foot, these movements are rarely "pure movements" but are always associated with each other, realizing inversion (combined movement of plantarflexion, supination and adduction) and eversion (combined movement of dorsiflexion, pronation and abduction), which allow the foot to adapt to all contact surfaces(7).

1.2.6 Function of muscles on the ankle joint

The order in which muscles are listed in Table 1 reflects their contribution in performing the movement(8). Innervation of each muscle is indicated in brackets.

Dorsiflexion	Plantarflexion	Pronation	Supination
Anterior tibialis (n. Fibularis profundus)	Triceps surae (n. Tibialis)	Peroneus longus (n. Fibularis superficialis)	Triceps surae (n. Tibialis)
Extensor digitorum longus (n. Fibularis profundus)	Peroneus longus (n. Fibularis superficialis)	Peroneus brevis (n. Fibularis superficialis)	Tibialis posterior (n. Tibialis)
Extensor hallucis longus (n. Fibularis profundus)	Peroneus brevis (n. Fibularis superficialis)	Extensor digitorum longus (n. Fibularis profundus)	Flexor hallucis longus (n. Tibialis)
	Tibialis posterior (n. Tibialis)	Peroneus tertius (n. Fibularis profundus)	Flexor digitorum longus (n. Tibialis)
	Flexor hallucis longus (n. Tibialis)		Anterior tibialis (n. Fibularis profundus)
	Flexor digitorum longus (n. Tibialis)		

Table 1: Function of muscles on the ankle joint

1.3 Gait cycle

Gait pattern may be defined as “a series of movements which form a coherent and energy-efficient motion which results in forward propulsion of the body"(9) It is a highly coordinated process that involves the central nervous system, the spinal cord, peripheral nerves, muscles, bones and joints. The science of studying human gait is called gait analysis. The gait cycle is the duration that occurs from the time when the heel of one foot strikes the ground to the time at which the same foot contacts the ground again(10). Normally it lasts 1-2 s.

1.3.1 Phases of gait

The gait cycle can be divided in two main phases: stance phase (60%) and swing phase (40%). Stance phase is defined as the time during which the limb is in contact with the ground and supporting the weight of the body. Swing phase is defined as the time period during which the limb is off the ground and advancing forward. Accordingly to Perry, J., and Burnfield, J. M. (2010)(11) stance and swing phases can be subsequently divided in the following phases (Fig. 4):

Stance phase includes:

- Initial contact (0-2%)
- Loading response (2-10%)
- Mid-stance (10-30%)
- Terminal stance (30-50%)
- Pre swing (50-60%)

Swing phase includes:

- Initial swing (60-73%)
- Mid swing (73-87%)
- Terminal swing (87-100%)

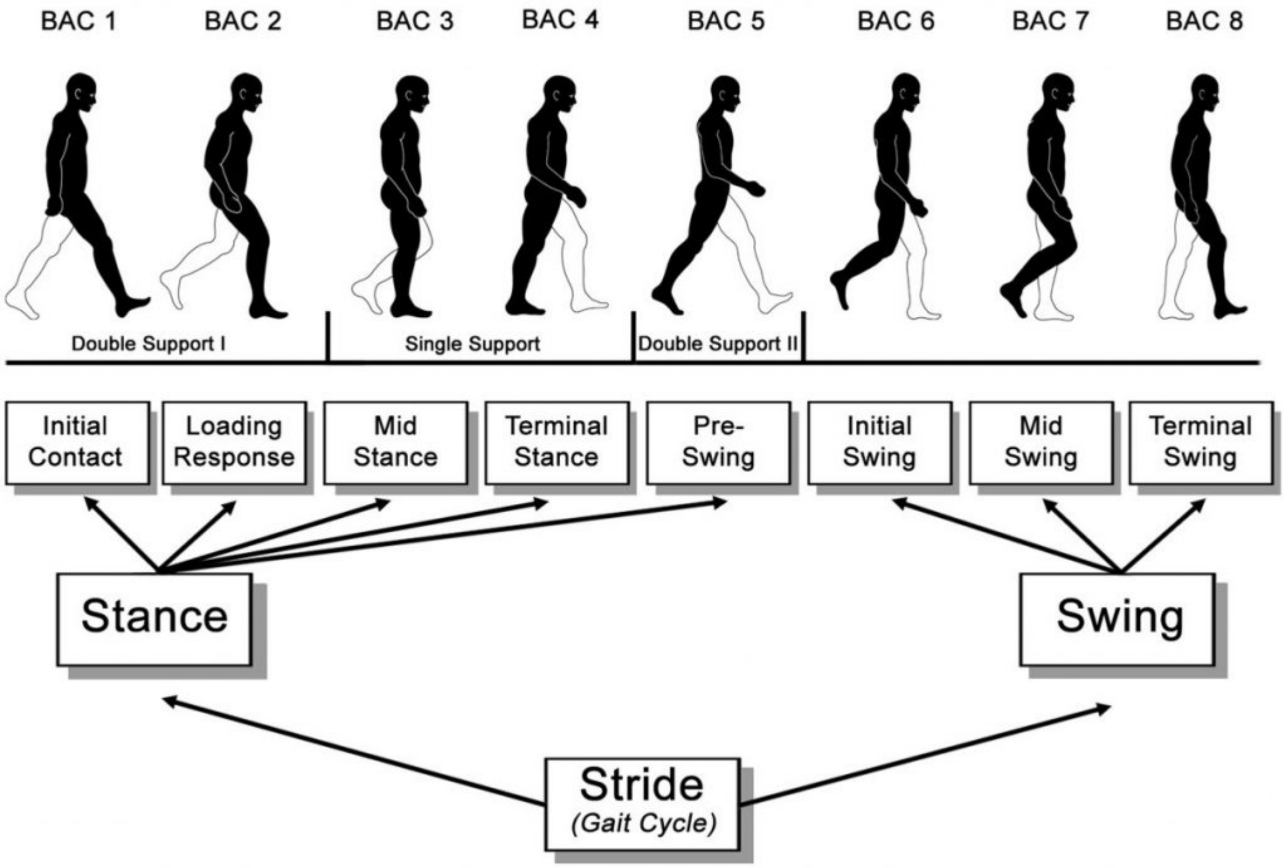


Figure 4: Phases of gait cycle based on the work of Perry and Burnfield (2010)

1.4 Lateral ankle sprain

As chronic ankle instability is a potential consequence of a first lateral ankle sprain, before dealing with CAI, some key information about lateral ankle sprains will be provided.

1.4.1 Mechanism of injury

The aetiology of lateral ankle sprain injury could be of two different types: in the first case ankle sprain is caused by explosive inversion or supination moment at the subtalar joint which is the result of an inappropriate foot positioning at initial contact. It has been demonstrated that when the foot is plantarflexed (Fig. 5) during touch down and the contact to the ground is made with the forefoot, the ground reaction force moment arm about the subtalar joint increase and cause sudden supination and ankle sprain injury(12).

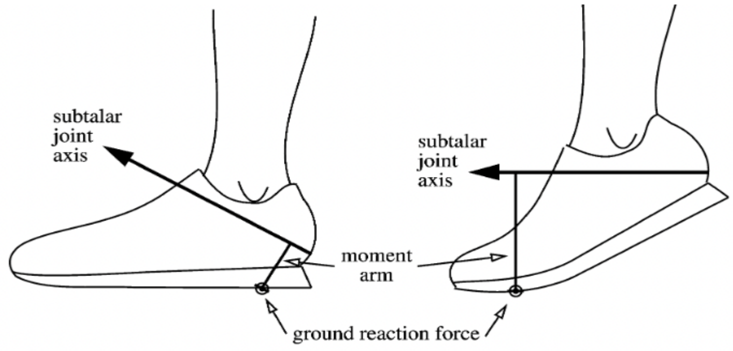


Figure 5 The moment arm of the horizontal component of the ground reaction force about subtalar joint when first contact is made with the heel (left) is smaller than the moment arm when the foot is plantarflexed and first contact is made at the toe (right)

Similarly, if at the touch down the foot is already in supination (Fig. 6), a greater ground reaction force at the subtalar joint can result in excessive supination. Another explanation of the mechanism of ankle sprain injury is the delayed reaction time of the peroneal muscles as dynamic stabilizers of the ankle(13). The peroneal longus and peroneal brevis have a role of pronators and their contraction opposes to the supination of the foot. In case the activation of the peroneal muscles is not fast enough to mitigate the sudden explosive supination motion, ankle sprains occur. Other mechanism of injuries, far less common than lateral ankle sprain, involves an increased eversion moment that result in a medial ankle sprain or a combination of external rotation and dorsiflexion which cause high ankle sprains (syndesmotic ankle sprains).

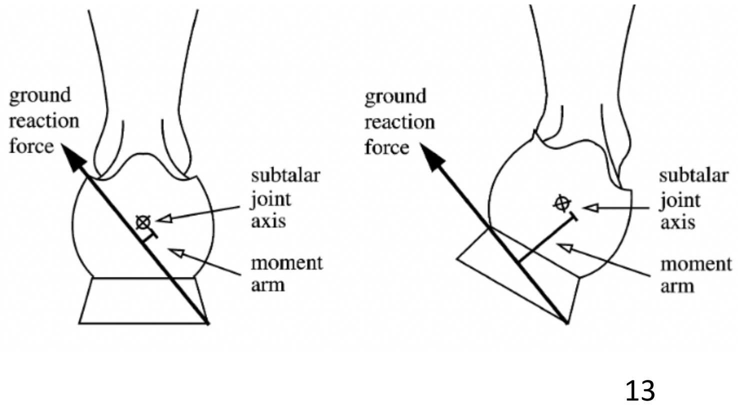


Figure 6 The moment arm of the groun reaction force about the subtalar joint whe the foot is flat (left) is smaller than th moment arm when the foot is supinate (right)

1.4.2 Classification grading systems

Many classification systems for ankle sprains have been developed over the years, among them, two grading systems have become the most common. A first grading system(14) focuses on a single ligament (usually ATFL) and distinguishes three grade of injury:

- Grade I microscopic injury without stretching of the ligament on a macroscopic level;
- Grade II characterised by stretching of the ligament which remains intact;
- Grade III complete rupture of the ligament.

Another grading system(14) consider the clinical severity of the injury classifying it in three clinical grades: mild, moderate and severe.

- Grade I (mild) characterised by little swelling and tenderness, minimal or no functional loss, and no mechanical joint instability;
- Grade II (moderate) has moderate pain, swelling, and tenderness over the involved structures; some joint motion is lost, and joint instability is mild to moderate;
- Grade II (severe) is a complete ligament rupture with marked swelling, haemorrhage, and tenderness; function is lost, and joint motion and instability are markedly abnormal.

1.4.3 LAS mid-term and long-term consequences

Resolution of primary inflammatory symptoms after an acute lateral ankle sprain usually take a short period of time and most individuals have a high likelihood of returning quickly to activity and to sport. However, the assumption that lateral ankle sprains have no consequences once the subacute phase has passed is inappropriate. Literature has widely demonstrated that who has experienced a first ankle sprain is likely to show disabling symptoms and residual deficits at follow-up evaluation. At 6-month follow-up Gerber et al. (15) have observed that out of 61 participants, only 72% of all patients with LAS presented with full function and 25% of patients still reported pain. Another study(16) demonstrated that residual impairments were present even at 7-year follow-up. They found that among 648 individuals with LAS, 72% of the subjects with residual disability reported that they were functionally impaired by their ankle, 32% still had pain, swelling or recurrent injury (three or more severe sprains/year), 19% were bothered by repeated inversion injuries. These data suggest that LAS is not an isolated acute injury and but deficits like ongoing pain, feelings of instability and sensorimotor impairments can last month and years after the first injury, leading to the development of CAI.

1.5 Chronic ankle instability

Chronic ankle instability (CAI) is a condition characterized by repetitive episodes or perceptions of the ankle giving way, ongoing symptoms such as pain, weakness, or reduced ankle range of motion (ROM), diminished self-reported function, and recurrent ankle sprains that persist for more than 1 year after the initial injury(17).

1.5.1 Prevalence of CAI

The high prevalence of CAI reported by literature and the economic burden it places on the health care system makes CAI a public health concern. Doherty et al.(3) found that 40% of patients who experienced a first-time ankle sprain had developed CAI at 12-month follow-up. If lateral ankle sprains are among the most common musculoskeletal injuries and the most prevalent injury among physically active individuals(18), a study(19) demonstrated that the prevalence of CAI was about 25% in collegiate and high school athletes with a previous history of injury. Ankle sprains, whether they are first-time or recurrent ankle sprains, are responsible for elevated direct (health care) costs and indirect (productivity loss) costs(16), and thus represent a public health concern. It is estimated that in the UK 1.5 million of people get access to the emergency department annually following an acute lateral ankle sprain. If considering that Cooke et al(20) estimated the costs of ankle sprains presenting at an emergency department in the UK to be £940, there would be more than 1.4 billion in annual costs for ankle sprains. However, these estimations are likely to underestimate the true costs associated with LAS given that many individuals after sustaining an ankle sprain may not present to an emergency department or seek medical care.(2)

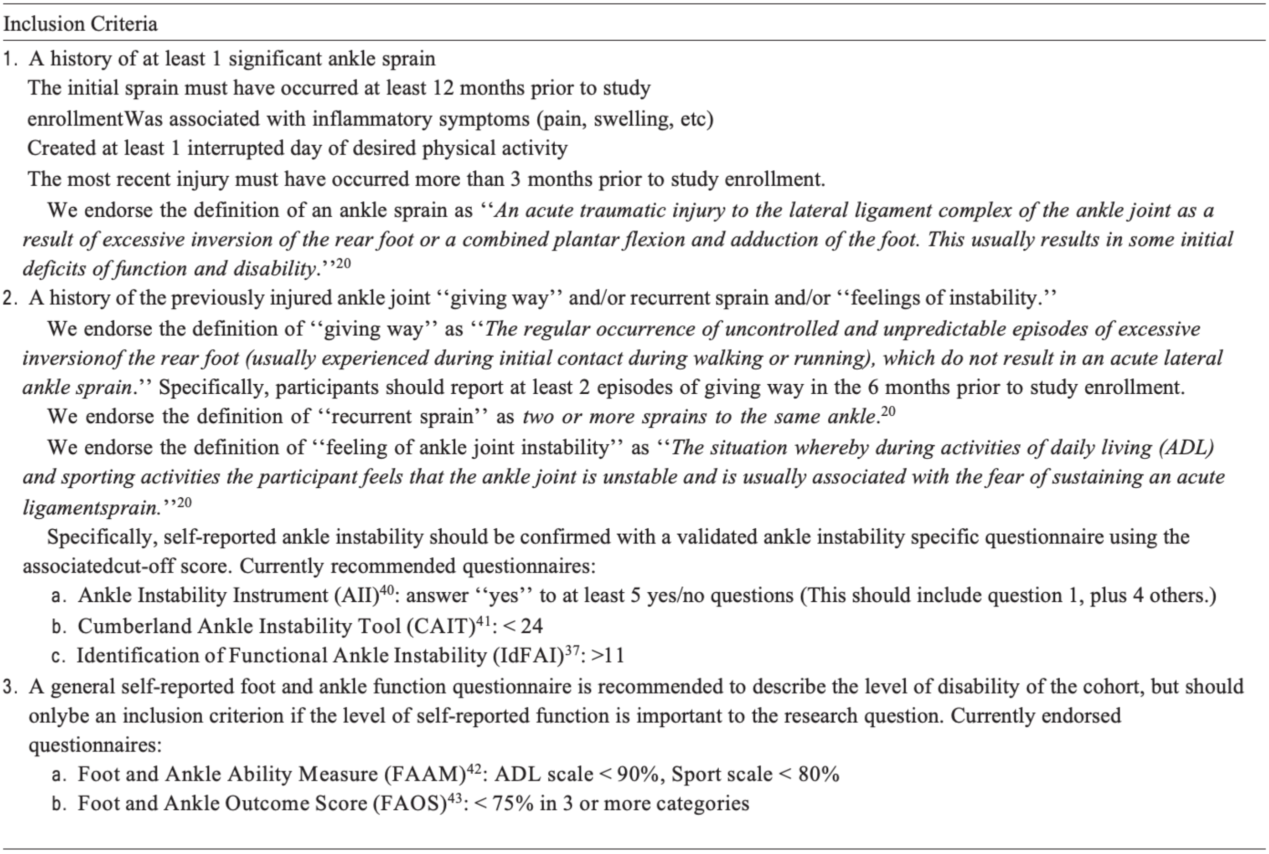
1.5.2 From lateral ankle sprain to chronic ankle instability

While the prevalence of CAI after experiencing a first LAS is well established, the mechanism underlying how individuals develop CAI is not clear. A first hypothesis concerns the lack of medical assessment and appropriate care. The culture of LAS being as an innocuous injury leads people not to seek any type of care supposing a short period of res twill be sufficient. Another possible factor to the development of CAI is the inadequate standard of care for LAS. What typically happens is to limit the management of LAS to the inflammatory phase and considering the injury resolved once pain is reduced and weight-bearing tolerated. However, the emphasis on a rapid return to activity and to sport before a complete healing has occurred, increases the risk to develop CAI and persistent disability. Lastly, there is a third hypothesis which attributes the onset of CAI at aberrant sensorimotor and neuromuscular patterns observed in CAI population. These neuromuscular deficits show that ankle sprain is not a local injury but produces modification within the central nervous system that rehabilitation should address. Alterations in balance, gait and movement patterns are thought to be responsible for placing the foot in a positioning which predisposes a person to recurrent ankle sprains. Current rehabilitation approaches have been found to be unable to improve these deficits(21).

1.5.3 Diagnosis

The diagnosis of CAI is based on the selection criteria for patients with chronic ankle instability published by the International Ankle Consortium(22). Its purpose was that of fill the gap within literature due to the heterogeneity and inconsistency in the terminology utilized to describe ankle instability and inclusion criteria for patients’ recruitment across studies. Therefore, the International Ankle Consortium proposed the establishment of accepted standards for participants selection criteria when conducting research on CAI. Standard inclusion and exclusion criteria are illustrated in Table 2 and 3(22).

Table 2. Standard Inclusion Criteria Endorsed, as a Minimum, by the International Ankle Consortium for Enrolling Patients that Fall Withinthe Heterogeneous Condition of Chronic Ankle Instability in Controlled Research



Inclusion Criteria

1. A history of at least 1 significant ankle sprain
   The initial sprain must have occurred at least 12 months prior to study
   enrollmentWas associated with inflammatory symptoms (pain, swelling, etc)
   Created at least 1 interrupted day of desired physical activity
   The most recent injury must have occurred more than 3 months prior to study enrollment.
   We endorse the definition of an ankle sprain as ‘‘*An acute traumatic injury to the lateral ligament complex of the ankle joint as a result of excessive inversion of the rear foot or a combined plantar flexion and adduction of the foot. This usually results in some initial deficits of function and disability*.’’[20]
2. A history of the previously injured ankle joint ‘‘giving way’’ and/or recurrent sprain and/or ‘‘feelings of instability.’’
   We endorse the definition of ‘‘giving way’’ as ‘‘*The regular occurrence of uncontrolled and unpredictable episodes of excessive inversionof the rear foot (usually experienced during initial contact during walking or running), which do not result in an acute lateral ankle sprain*.’’ Specifically, participants should report at least 2 episodes of giving way in the 6 months prior to study enrollment.
   We endorse the definition of ‘‘recurrent sprain’’ as *two or more sprains to the same ankle*.[20]
   We endorse the definition of ‘‘feeling of ankle joint instability’’ as ‘‘*The situation whereby during activities of daily living (ADL) and sporting activities the participant feels that the ankle joint is unstable and is usually associated with the fear of sustaining an acute ligamentsprain.*’’[20]
   Specifically, self-reported ankle instability should be confirmed with a validated ankle instability specific questionnaire using the associatedcut-off score. Currently recommended questionnaires:
   a. Ankle Instability Instrument (AII)[40]: answer ‘‘yes’’ to at least 5 yes/no questions (This should include question 1, plus 4 others.)
   b. Cumberland Ankle Instability Tool (CAIT)[41]: < 24
   c. Identification of Functional Ankle Instability (IdFAI)[37]: >11
3. A general self-reported foot and ankle function questionnaire is recommended to describe the level of disability of the cohort, but should onlybe an inclusion criterion if the level of self-reported function is important to the research question. Currently endorsed questionnaires:
   a. Foot and Ankle Ability Measure (FAAM)[42]: ADL scale < 90%, Sport scale < 80%
   b. Foot and Ankle Outcome Score (FAOS)[43]: < 75% in 3 or more categories

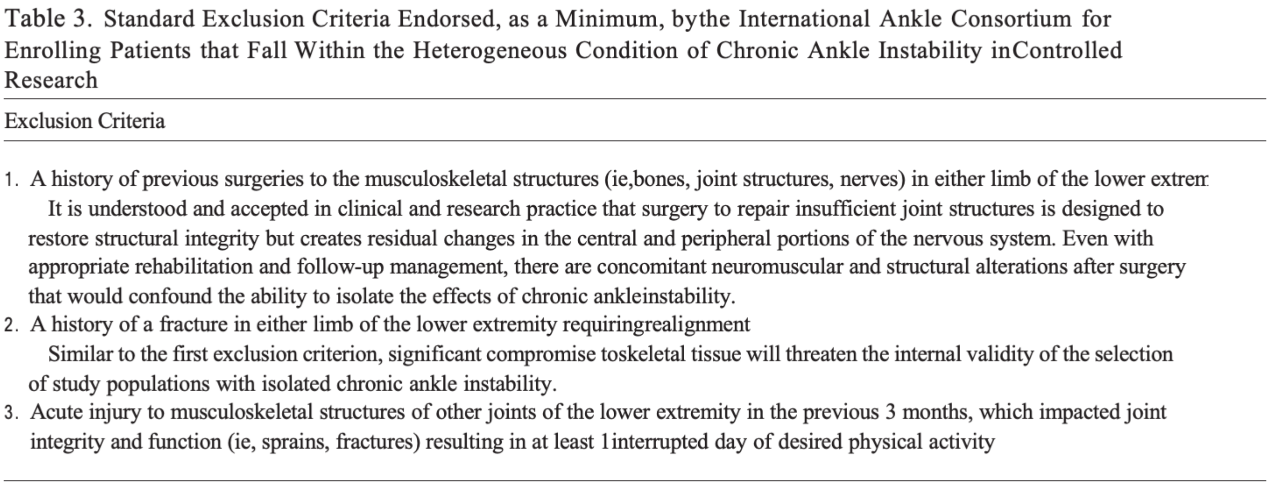


Table 3. Standard Exclusion Criteria Endorsed, as a Minimum, bythe International Ankle Consortium for Enrolling Patients that Fall Within the Heterogeneous Condition of Chronic Ankle Instability inControlled Research

Exclusion Criteria
1. A history of previous surgeries to the musculoskeletal structures (ie,bones, joint structures, nerves) in either limb of the lower extrem It is understood and accepted in clinical and research practice that surgery to repair insufficient joint structures is designed to restore structural integrity but creates residual changes in the central and peripheral portions of the nervous system. Even with appropriate rehabilitation and follow-up management, there are concomitant neuromuscular and structural alterations after surgery that would confound the ability to isolate the effects of chronic ankleinstability.
2. A history of a fracture in either limb of the lower extremity requiringrealignment Similar to the first exclusion criterion, significant compromise toskeletal tissue will threaten the internal validity of the selection of study populations with isolated chronic ankle instability.
3. Acute injury to musculoskeletal structures of other joints of the lower extremity in the previous 3 months, which impacted joint integrity and function (ie, sprains, fractures) resulting in at least 1interrupted day of desired physical activity

1.5.4 CAI impairments

CAI may manifests with many mechanical and functional impairments, Donovan and Hertel(23) synthesized the vast majority of them, classifying the deficits in four major domains: range of motions, strength, postural control and functional tasks.

1.5.4.1 Range of motion

Individuals with CAI show impaired arthrokinematics at the ankle complex. Immediately after a LAS there is a restriction in ankle dorsiflexion, but this deficit is unlikely to persist after the subacute phase and generally passive dorsiflexion ROM returns to baseline levels. However, two characteristics observed in CAI are an anterior displacement of the talus and a restricted anterior-to-posterior glide of the talus on the tibia. These restrictions can be responsible for limited dorsiflexion of the talocrural joint(17). Also, there can be an anterior and inferior displacement of the distal fibula. This position fault of the fibula places the ATFL in a slacker position at rest which allows greater movement of the talus before ATFL becomes taut, leading to recurrent instability.

1.5.4.2 Strength

Muscle weakness in isometric inversion, eversion and plantarflexion of the involved limb are well documented in CAI. Strength deficits limit the ability of muscles surrounding the ankle to provide dynamic stability to the joint. Other deficits have been reported also at the proximal joints of the knee and hip(17).

1.5.4.3 Postural control

Postural control described as the act of maintaining, achieving, or restoring a state of balance during any upright stance (23). It is typically assessed through single limb stance (static balance) and the Star Excursion Balance Test (dynamic balance). During single limb stance CAI people have been reported(24) to use more of a “hip strategy” to maintain unilateral stance than the normal “ankle strategy” consisting of rapid pronation and supination of the foot in an effort to keep the body's center of gravity above the base of support. In addition, CAI people rely more on visual input rather than on somatosensory information compared to healthy control. During the SEBT, CAI patients are generally unable to reach as far as healthy control.

1.5.4.4 Functional tasks

During walking CAI population exhibit an altered gait pattern characterized by increased ankle inversion, greater plantarflexion of the foot relative to the tibia, a laterally deviated center of pressure, and alteration in peroneus longus activation(17). Such alterations are thought to contribute to recurrent ankle sprains, the feeling of instability and self-reported disability. Gait biomechanics is characterised by increased lateral loading and increased contact time of the lateral aspect of foot with a center of pressure laterally deviated compared to healthy controls. The increased pressure on the lateral column during the stance phase in due to a more inverted foot position prior to initial contact. This improper foot positioning with CAI may cause the activation of the peroneus longus during the swing phase to correct foot position, whereas healthy subjects do not activate their peroneus longus until midstance(25). However, this compensation mechanism does not appear to be effective at restoring normal frontal plane alignment. Finally, the altered biomechanics during gait results in higher vertical ground reaction force, vGRF loading rates and reduced time to peak vGRF which can lead in the long-term to cartilage damage and the advent of post-traumatic osteoarthritis(26).

Biomechanical alterations during running are comparable to those seen during walking.

During single leg jump-landing task CAI people show a lower activation of peroneal muscles before landing, and altered vertical ground reaction force variables including greater peak vertical GRF and shorter time to peak vertical GRF compared to healthy subjects(27). Furthermore, they demonstrate increased inversion at the ankle and increased flexion at the knee and hip.

1.5.5 Clinical practice guidelines for CAI rehabilitation

In 2021 the American Physical Therapy Association published updated clinical practice guidelines(4) for lateral ankle ligament sprains providing rehabilitation recommendations for both acute lateral ankle sprain and chronic ankle instability. The main recommendations for CAI treatment are the following:

1) External support including bracing, taping, and insoles as a sole treatment is not recommended because is unable to promote improvements in balance and postural control in people with CAI;
2) Therapeutic exercise including balance retraining, postural re-education, neuromuscular training, and strengthening of ankle muscles is recommended as it is effective in improving dynamic postural stability and patient-perceived stability;

3) Manual therapy is effective in producing short-term effects that may be essential to an initial return to activity participation;
4) Interventions that combine two or more treatments, selected based on patient-centered factors, are useful related to balance training alone in promoting functional improvements;
5) Interventions to address psychological factors during the course of rehabilitation are recommended as education, encouragement, goal setting, and fear mitigation, may facilitate return to function in this patient population.

1.6 Biofeedback in neuromotor rehabilitation

Biofeedback, also known as augmented feedback is described as the technique of instrumentation to reveal instantaneously to patients and therapists certain physiologic events and to teach the patients to control these otherwise involuntary events by manipulating the displayed signals(28). In other words, biofeedback allows to make covert physiological process more overt. Several studies(29)(21)(30) adopted external biofeedback to fed back to participants information about plantar pressure which, otherwise, patients would not be able to perceive (or even to observe looking at their foot in a mirror). Biofeedback can be classified according to the type of stimulus they provide in visual, auditory, and haptic feedback, but their functioning is similar: they provide a sensory cue when a set threshold is overpassed, informing the patient of how the positioning of the foot at ground contact was. This strategy allows both "forward modeling" by providing to patient sensory cues which inform him about the consequences of actions, and "inverse modeling" promoting adaptive strategies to be adopted(28). Augmented feedback can be classified according to the type of stimulus provided in visual (screens, displays, laser pointer), auditory (speakers, headphones) or haptic feedback. Feedback strategy may also be categorized based on the point in time at which feedback is provided: during motor task (concurrent feedback) or after it (terminal feedback).(31) While the ability of augmented feedback to enhance motor learning is well established, the neurological mechanism underlying the effectiveness of biofeedback strategy is still unclear. Accordingly to Basmajian, there are two possible explanations: one refers to the development of new cerebral pathways or underused existing synapses are activated following auxiliary feedback.(32) Overall, it is generally agreed that biofeedback strategy promote motor learning by enhancing neural plasticity. Lastly, contemporary evidence on motor learning suggest that greater improvements are gained performing functional activities and task-oriented training. Therefore, biofeedback strategies should be linked to functional goals rather than static control of muscular or joint activity. (28) On the basis of the training task and the therapeutic functional goal depend on the choice of a different type of biofeedback and the time at which it is provided.

1.6.1 External visual feedback

Some authors adopted external visual feedback to fed back information regarding foot positioning and plantar pressure during stance phase (21)(30). In order to provide the visual feedback, different devices may be utilized, among them will be mentioned a laser pointer and a screen providing the feedback. In the first case, the device consists of a laser pointer (Fig.7) fastened onto a strap and secured on the dorsal aspect pf the involved foot. The battery pack was secured to the lower limb so as not to impede normal ankle mechanics or range of motion.

Once the laser has been attached, participants are required to stand on a treadmill with their foot shoulder-width apart and in a neutral position with the laser projecting a cross line on to the wall in front of the treadmill. This neutral position of the foot unique for each participant is marked with tape to provide a piece of reference on the wall (Fig.8). Once participants started walking, the laser device provide to them real-time external visual feedback on the positioning of the foot during stance phase compared to the cross-line of tape indicating its neutral position.

Figure 7: Visual feedback provided by a laser pointer (21)

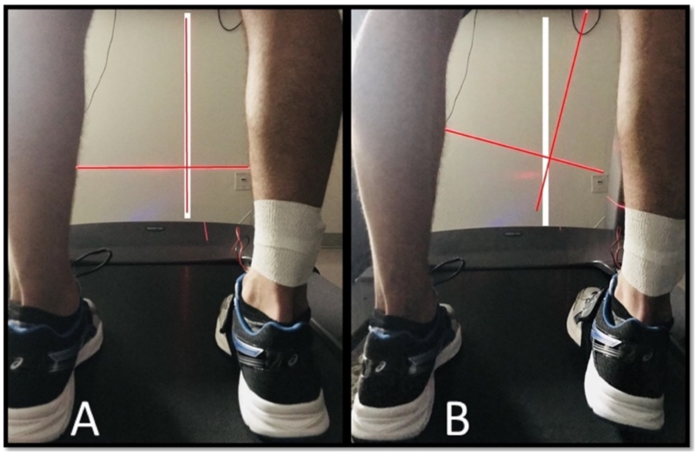


Figure 8: Relation of the cross-line projected by the laser and the center of pressure location (21)

Another biofeedback tool to provide external feedback about the ankle inversion ankle at initial contact consists in projecting the ankle inversion angle as an oval on to a screen (Fig.9). When participants exceeded a set inversion threshold, the biofeedback oval turned from green to red.

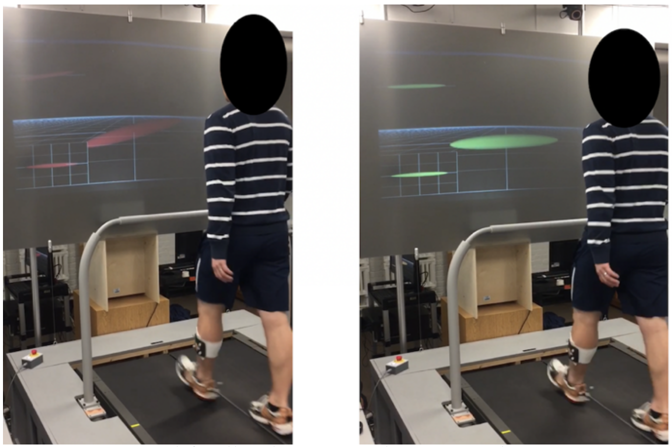


Figure 9: Visual feedback projected as an oval on to a screen (33)

1.6.2 Auditory biofeedback

Plantar pressure measures can be fed back also by auditory feedback. The auditory biofeedback device (Fig.10) was made of a force sensitive resistor which was placed inside the shoe, under the head of the 5th metatarsal, the battery potentiometer and buzzer which were secured on the top of the shoe. This device needs to be calibrated by defining a threshold. The procedure to set the threshold consists in rocking from heel to toes while standing on one limb and placing the total weight on the sensor until the first-time continuous noise was elicited by the buzzer. When a person's vertically directed force exceeded the threshold of the force sensor, the device elicited a noise.

Figure 10: Auditory feedback device (30)

1.6.3 Vibration biofeedback

Vibration feedback about plantar pressure is provided through a device made of a force sensor resistor, the electronics and battery (Fig. 11). The former is placed in the shoe under the fifth metatarsus and set such as standing on the involved limb triggered the feedback but standing on two limbs did not. The latter were secured on the top of the shoe. Finally, a vibration motor was placed on the lateral malleolus. The vibration motor turns on when the pressure under the lateral foot exceeded the threshold.

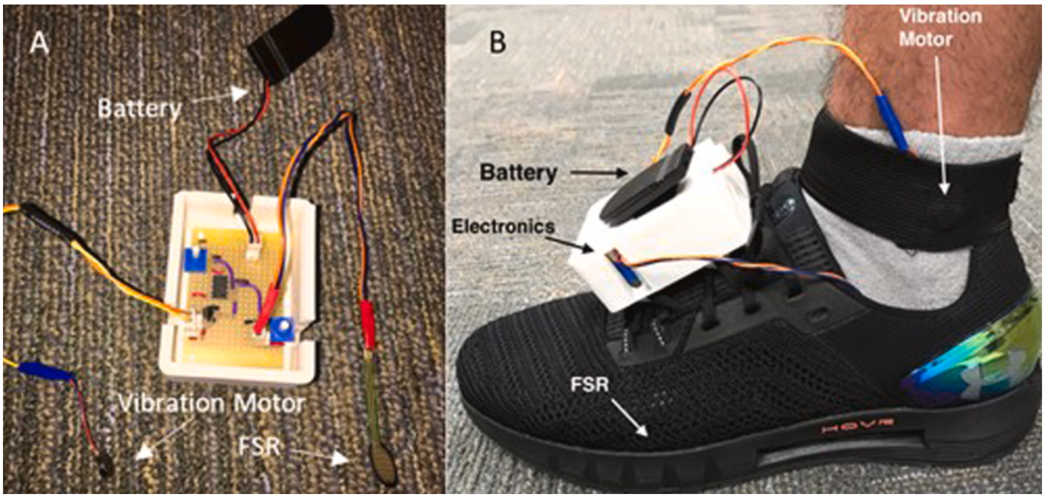


Figure 11: Vibration biofeedback tool and its components (26)

2 MATERIAL AND METHODS

2.1 Objective

The purpose of this investigation is to examine the effects of biofeedback interventions on muscular activity and biomechanics during gait and functional tasks in individuals with chronic ankle instability. The hypothesis is that, thanks to external biofeedback such as haptic or auditory or visual feedback, it is possible to (1) modify the plantar pressure distribution and result in a medial shift of the center of pressure during gait as well as functional tasks (walking, step-down, lunge, lateral hops) (2) reduce the invert position of the foot that has been demonstrated in people with CAI (3) modify the altered activation of the peroneus longus (4) impact on ankle cartilage measures and (4) improve patient-reported outcome measures. Preliminary research was conducted to collect information and updated data on ankle sprain mechanism and classification and ankle sprain and CAI rehabilitation. Next, a literature investigation was performed to study the rationale and the efficacy of biofeedback interventions as a new rehabilitation strategy for CAI.

2.2 Research strategy

The first step to start the literature review was to determine the research question that this work aims to answer: i.e, to understand which are the effects of interventions with biofeedback in people with CAI. Successively, the research question was elaborated through the PICO acronym where:
P (population) > adult people with chronic ankle instability according to the selection criteria for CAI published by the International Ankle Consortium;
I (intervention) > external feedback interventions (auditory\haptic\visual feedback);
C (comparison) > rehabilitation interventions without external feedback or none;
O (outcome) > at least one among patient self-reported outcomes and clinically-oriented measures such as plantar pressure distribution, center of pression location, ankle inversion angle, vertical ground reaction force, joint contact forces and talar cartilage measures.

The primary search for articles was conducted in the following databases: Pubmed, PEDro, Cochrane Library and Scopus. In addition, reference lists of each included paper were also checked to identify further eligible studies. The search strategy was based on the combination of different keywords such as ankle instability(1), plantar pressure(2), gait training(3), feedback (3), biofeedback(4).
The keywords were associated with the Boolean operators “AND” or “OR” to create a string.
The following string was utilized on Pubmed, Cochrane Library and Scopus:

("ankle instability") AND ("plantar pressure" OR "gait training" OR biofeedback OR feedback)

As the aforementioned string did not find any results on PEDro database, another string was elaborated and launched on this database: ("ankle instability" AND gait)

Next, the studies collected from the different databases were screened first by title and then by abstract. Successively, the full text of the articles eligible from abstract screening were red and only the articles that met the inclusion and exclusion criteria were included.

2.3 Inclusion and exclusion criteria

To be eligible, the articles had to meet the following inclusion criteria. Population had to meet the established criteria for CAI as recommended by the International Ankle Consortium:

- one significant ankle sprain more than 1 year prior to enrollment, repeated episodes of the ankle "giving way" / a history of more than one ankle sprain with the initial sprain occurring greater than one year prior to study onset;
- self-reported dysfunction (Foot and Ankle Ability Measure (FAAM) Sport <85%, Foot and Ankle Ability Measure (FAAM) activities of daily living subscale ≤90%), and feelings of perceived instability (Identification of Functional Ankle Instability (IdFAI) >10);
- participants were physically active (at least 20 minutes of exercise 3 times per week).

In addition, the intervention had to use a biofeedback instrument, which could be a visual, auditory, or haptic biofeedback. The outcome measures had to include at least one among plantar pressure measure, center of pressure (COP) location, talar cartilage measure, vertical ground reaction force and joint contact force, self-reported outcome. Furthermore, the articles were selected by the publication type: case reports, clinical trials, clinical studies, and comparative studies were included. The text was required to be in English and lastly, full text version of the articles needed to be available.

Exclusion criteria were a history of previous lower extremity surgery, a lower extremity fracture or acute injuries within the past 3 months, history of ankle sprain within 6 weeks of data collection, the absence of other lower extremity injuries or pathologies and the participation during the study period in other rehabilitation program.

2.4 Study selection

The process of selection of the studies is illustrated in the following flow chart (Fig. 12).

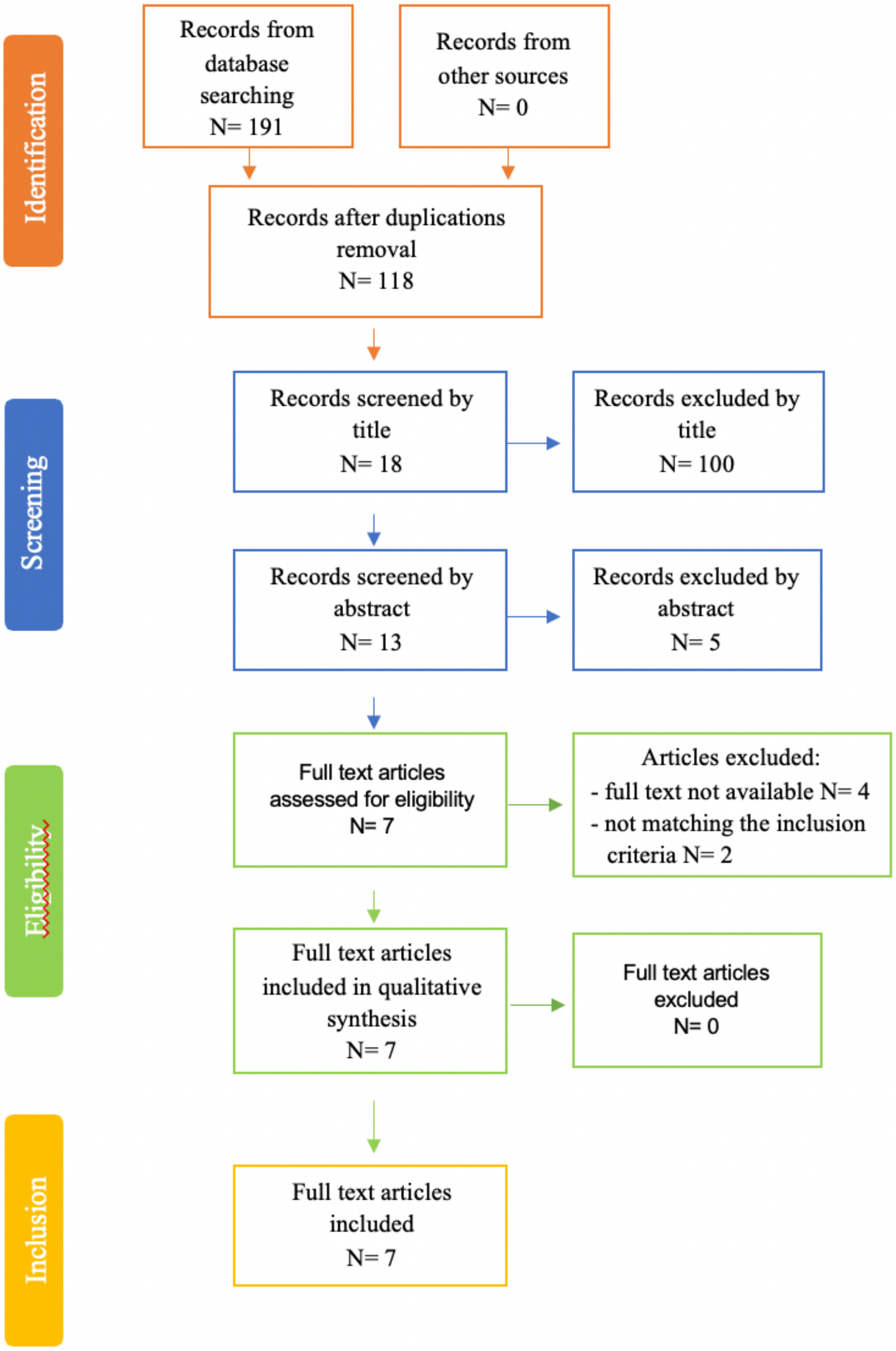


Figure 12: Flow chart of the articles' selection process

The research started in March 2022 and has continued until July 2022. 191 articles were collected from the research on MEDLINE, PEDro, Scopus and Chocrane Library databases. After the elimination of the duplicates from 180 articles, 118 remained. The 118 articles left were screened firstly by the title and then by the abstract reading and 13 articles were assessed as eligible after the screening phase. Successively 4 articles of the 13 left were excluded because the full text wasn't available and 2 more articles for not meeting the inclusion criteria as the intervention didn't include the use of external biofeedback. At this point, 7 articles were read entirely and were included in the qualitative evaluation. All of them met the inclusion criteria and thus were included in the research.

2.5 Quality assessment

The quality of the papers was independently evaluated by two reviewers (SDM, RDM). For each paper were assessed fourteen criteria belonging to the following seven sections: 1) aim of the work, 2) inclusion criteria (selection bias), 3) data collection and processing (performance bias), 4) data loss (attrition bias), 5) outcomes (detection bias), 6) presentation of the results, and 7) statistical approach. Each item listed in Table 4, was scored from 0 to 2 by each reviewer, considering if the goals were not met (0), partially met (1), or fully met (2). Then the individual criteria scores were summed and averaged among reviewers. An article was included if the final score exceeded 60% of the maximum score (>17).

Table 4: Quality check items

AIM OF THE WORK
1. Description of a specific, clearly stated purpose
2. The research question is scientifically relevant

INCLUSION CRITERIA
3. Description of inclusion and/or exclusion criteria

DATA COLLECTION & PROCESSING
4. Data collection is clearly described and reliable
5. Data processing is clearly described and reliable
6. Algorithms are clearly described and referenced

DATA LOSS
7. Drop-outs < 20%

OUTCOMES
8. Outcomes are topic relevant
9. The work answers the scientific question stated in the aim

PRESENTATION OF THE RESULTS
10. Presentation of the results is sufficient to assess the adequacy of the analysis
11. The main findings are clearly described

STATISTICAL APPROACH
12. Appropriate statistical analysis techniques
13. Clearly states the statistical test used
14. Actual probability values reported for the main outcomes

2.6 Data extraction form

A standardized form was created to extract data from the eligible papers. The following data were included in the extraction form: 1) first author and year of publication, 2) participant characteristics, 3) biofeedback type, 4) procedures and 5) outcomes.

An example of the data extraction form is provided in Table 5.

Table 5: Data extraction form

Reviewer		**Date**		**Checked by**	
List of authors					
Year of Publication					
Journal					
Publication type	Full paper/other				
Fate	Inclusion/exclusion/decision pending				
Research question					
Aim					
Partecipants	Number/sex/age interval/control group				
Biofeedback type	Visual/auditory/haptic feedback				
Instrumentation	EMG/ultrasound/plantar pressure systems				
Intervention					
Outcome measures					
Results in brief					
Reasons for exclusion					

3 RESULTS AND DISCUSSION

In this chapter a first paragraph is dedicated to an overall view of the included articles and the relevant outcome measures. Successively the results achieved by the studies will be described and discussed according to each outcome measure: i.e., explaining whether or not the effects of biofeedback interventions on plantar pressure are retained; which is the biofeedback impact on patient-reported outcome and talar cartilage measures; and, finally, the results of a multi-session biofeedback program and a comparison of the different types of biofeedback are described.

3.1 Overview of the articles included in the work

Current rehabilitation methods have been successful in treating some functional deficits like strength, balance and neuromuscular impairment showed by people with CAI, but biomechanical gait alterations remain unchanged (36). People with chronic ankle instability show altered temporal gait parameters as well as altered kinetics and kinematics during gait and functional activities (37). In addition, there is an increase in percent activation time for the peroneus longus across the gait cycle for people with CAI when compared to healthy controls. Previous research suggest that the modifications observed during gait cycle may be correlated to the high recurrence of ankle sprains as well as the perceived instability reported as a “giving-away” sensation which are characteristics of CAI condition and can lead to a continuum of disability. Therefore, research has been undertaken to find out a rehabilitation strategy capable of modifying biomechanics alterations, to be incorporated into rehabilitation programs for people with CAI.

The research, updated to July 2022, was conducted on the following databases: Chocrane Library, MEDLINE, PEDro and Scopus. 28 articles were found on the Cochrane Library database, 67 on Pubmed, only 6 articles on PEDro and other 90 on Scopus. From a total of 191 articles, 73 articles were eliminated after the duplication removal. The remaining118 studies were screened first by title and then by abstract: 100 records were excluded after the title screening and other 5 after reading the abstract. Thirteen articles were retained for further evaluation after the screening phase. Among those, four articles were excluded because their full text version was not available and other two articles for not meeting the inclusion criterium regarding the adoption of biofeedback in the intervention. Therefore, seven articles were passed to the quality assessment, which was conducted according to the criteria in Table 4. All the studies reached the minimum score (score > 17) to be included in this work. The articles included are reported in Table 6.

QUALITATIVE ASSESSMENT		2016, L. Donovan	2019 D.M. Torp	2020 R.M. Koldenhoven	2021 K.G. Migel	2021 J. Jang	2021 D.M. Torp	2022 D.M. Torp
AIM OF THE WORK	Description of a specific, clearly stated purpose	2	2	2	2	2	2	2
	The research question is scientifically relevant	2	2	2	2	2	2	2
INCLUSION CRITERIA	Description of inclusion and/or exclusion criteria	2	2	2	2	2	2	2
DATA COLLECTION & PROCESSING	Data collection is clearly described and reliable	2	2	2	2	2	2	2
	Data processing is clearly described and reliable	2	2	2	2	2	2	2
	Algorithms are clearly described and referenced	2	2	2	2	2	2	2
DATA LOSS	Drop-outs < 20%	1	2	1	2	2	2	0
OUTCOMES	Outcomes are topic relevant	2	2	2	2	2	2	2
	The work answers the scientific question stated in the aim	2	2	2	2	2	2	2
PRESENTATION OF THE RESULTS	Presentation of the results is sufficient to assess the adequacy of the analysis	2	2	1	2	2	2	2
	The main findings are clearly described	2	2	2	2	2	2	2
STATISTICAL APPROACH	Appropriate statistical analysis techniques	2	2	2	2	2	2	2
	Clearly states the statistical test used	2	2	2	2	2	2	2
	Actual probability values reported for the main outcomes	2	2	2	2	2	2	2
TOTAL SCORE		27/28	28/28	26/28	28/28	28/28	28/28	26/28

Table 6. Articles included in this work

Results obtained by the studies included in this research, demonstrate the effectiveness of biofeedback interventions in CAI rehabilitation which caused significant clinical improvements at least on the short-term. However, when analysing the articles, we ought to consider the heterogeneity of the articles studied. First and foremost, the articles differ by the biofeedback type chosen by the authors, which could be a visual, haptic, or auditory feedback. It is likely to think that different external feedback impact differently on patients' task performance. Articles, then, differ by the kind of intervention performed and the data collection period of time. Some articles adopted the biofeedback tool when walking on a treadmill, other compared biofeedback effectiveness while walking inside on a treadmill and outside, another article used the biofeedback technology during functional tasks. Data collections were performed during the intervention by some authors, immediately after the conclusion of the intervention and/or after a determined period of time by other who wanted to measure retention effects. Lastly, not in all studies results gathered from people with CAIwere compared with those from a healthy control group.

3.1.1 Outcome measures

3.1.1.1 Clinically oriented measures

Clinically oriented measures utilized to describe the effects of biofeedback tools in CAI rehabilitation are mainly related to plantar pressure measures and COP location, the ankle vertical ground reaction force (vGRF) and joint contact force (JCF). Each of these includes a series of parameters that will be briefly examined and explained.

Plantar pressure measures assess the distribution of forces over the sole of the foot during the stance phase and is useful as it provides detailed information specific to each region of contact. Pressure distribution measurement include the following variables:

- Contact area (cm^2) represents the area in each region of the plantar surface in contact with the ground during stance phase (29)(21)(30);
- Contact time (ms) is described as the amount of time spent by each region in contact with the ground during the stance phase (29)(21)(30);
- Force-time integral (N*s) describes the length of time the force is applied to a particular area of the foot (30);
- Maximum force (N) is the highest value of force generated in each region of the foot (30)(34);
- Peak pressure (kPa) is described as the maximum pressure produced in a region of the foot during the stance phase and measured in kilopascals (kPa). The period of time needed to reach the peak pressure is called time to peak pressure (s) (29)(21)(30)(34);
- Pressure time integral (kPa∗s) was calculated as the total pressure (kPa) in a region multiplied by the amount of time (s) spent in stance (29)(21)(30).

Associated with plantar pressure measures, there is the assessment of the center of pressure (COP) location. The COP on the plantar surface of the foot is defined as the point of location of the vertical ground reaction force vector. The assessment of COP location during the stance phase is conducted through the analysis of the confidence ellipse area, mean velocity and COP gait line.

- The confidence ellipse area (cm^2) indicates the amount of movement of the COP and the direction of its movements (30);
- The mean velocity (cm/s) represents the total distance traveled by the COP over time (30);
- The COP gait line is the trajectory the COP follows during gait (21)(34)(35);

Ankle vertical ground reaction force (vGRF) is the force exerted by the ground on a body in contact with it. Typically, the vertical GRF consists of a first peak as heel comes into contact with the ground (impact peak) and a second peak during pushing-off (propulsive peak).

Vertical ground reaction force (26) variables are:

- The impact peak vGRF (N/BW) is obtained within the first 50% of the stance phase, with BW being the body weight;
- Time to impact peak vGRF (s) is defined as the time from initial contact to the impact peak vGRF;

- The impact vGRF loading rate (BW/s) is calculated by dividing the rise in force from initial contact to the impact peak vGRF by time to impact peak and then normalizing the quotient to gait velocity (m/s) and body weight;
- The propulsive peak vGRF (N/BW) is obtained from the last 50% of the stance phase;
- Time to propulsive peak vGRF (s) is calculated by the time from initial contact to the propulsive peak vGRF;
- The propulsive loading rate (BW/s) is defined by dividing the rise in force from the lowest vGRF point between the impact and propulsive peaks (i.e. negative peak) to the propulsive peak vGRF by time between the negative and propulsive peaks.

Joint contact force (JCF) (26) variables are:

- Peak JCF (N/BW) is the is the maximum force applied on the ankle articular surface during stance phase;
- Impulse JCF (BW*s) is calculated by integrating the stance phase of the ankle JCF waveform;
- Loading rate JCF (BW/s) is the maximum loading rate during the second half of stance (i.e. 51-100% of the stance phase).

3.1.1.2 Patient-reported outcome measures (PROs)

Patient-reported outcomes (33) included the following scales:

Foot and Ankle Ability Measure Activities of Daily Living (FAAM-ADL and FAAM-Sport)

FAAM is a questionnaire of a total of 29 item divided into two subscale which can be complete either together or separately.

- ADL subscale (21 items) assess the difficulties in the lower limb functions and their impact on activities of daily living
- Sport subscale (8 item) assess the difficulties in more complex activities essential to sport practice

A score from 0 to 4 is attributed to each item, 0 indicate the complete incapacity to do an activity; 4 indicate no difficulties in performing an activity. In addition, at the end of each subscale patients are required to indicate a percentage of their current functional ability.

Psychometric measure: reliability 0,89 (ADL subscale) e 0,87 (sport subscale). Minimally clinically important difference (MCID): 8 points for ADL subscale; 9 points for sport subscale.

3.1.1.2.1 Global Rating of Change (GROC)

GROC is a single-item questionnaire used to measure improvements in a patient’s condition after the beginning of a treatment. Patients are required to indicate their level of well-being on a 15 points scale (from -7 to 7). Test-retest reliability, evaluated with the Intraclass Correlation Coefficient (ICC) is very good (ICC = 0.90). Minimal clinically important difference 2 points.

3.1.1.2.2 Identification of Functional Ankle Instability (IdFAI)

IdFAI is meant to determine if a person has functional ankle instability. It includes 10 items. The score for each item goes from zero to four. Reliability 0.92; test–retest reliability (ICC= 0.92).

3.1.1.2.3 International Physical Activity Questionnaire (IPAQ)

Is 27 items measure of the level of physical activity. Duration and frequency of physical activity is measured in 5 domains: job-related, transportation, housework, sport and leisure time, time spent sitting. Score is expressed in three levels of physical activity: inactive/low, moderate, high. Test-retest reliability for overall score (ICC=0.81)

3.1.1.2.4 Patient Specific Functional Scale (PSFS)

Measure the level of functioning in 5 activities chosen by the patient.

Patients choose up to five activities they are unable or have difficulties to perform and rate the current level of difficulty associated to each activity from 0 to 10, where zero represents "unable to perform" and ten represents "able to perform at prior level". Following the intervention patients rate again each activity. Minimal clinically important difference for each activity: 3 points; Test-retest reliability: ICC=0.82.

3.1.1.2.5 Scale of Kinesiophobia (TSK)

TSK evaluates fear of movement, fear of physical activity, and fear avoidance.

It is composed by two subscales:

- Activity avoidance (AA): reflection of activity that may result in an increase in pain or cause injury
- Somatic focus (SF): reflection of beliefs and underlying serious conditions

It comprises a total of 17 items. The score range for 1 to 4 where (1) means strongly disagree, (2) disagree (3) agree and (4) strongly agree. The total score of the scale range from 17- 68, where 17 means no kinesiophobia, 68 means severe kinesiophobia. Test-retest reliability: ICC = 0.887.

3.1.1.3 Imaging

Surface electromyography (29)(33) was conducted on the muscles responsible of altering frontal plane ankle mechanics: anterior tibialis, peroneus longus, medial gastrocnemius, and gluteus medius. Ultrasound (34) was used to study talar characteristics.

3.1.1.4 Other

Ankle inversion angle (33) measured with 3-D kinematics of the ankle.

Strength (33) was assessed by isometric strength of ankle dorsiflexion, plantarflexion, inversion, eversion, 1st toe flexion, toes 2-5 flexion, hip abduction and hip extension.

Static balance (33) was measured with single limb balancing trials on a force plate with eyes open, and again with eyes closed. Whereas dynamic balance was assessed using the SEBT in the anterior, posteromedial, and posterolateral directions.
Passive ankle ROM (33) was assessed using a standard plastic goniometer to measure dorsiflexion, plantarflexion, rearfoot inversion, and eversion.

Overall, adopting a biofeedback tool in CAI patients' rehabilitation resulted useful in diminishing the plantar pressure on the lateral column of the foot and shifting the center of pressure location more medially, and in modifying the ankle frontal plane so that the inverted position of the foot was reduced. Gait retraining with a biofeedback showed positive effects on the vertical ground reaction force and joint contact force. Patient reported outcome measure improved after a rehabilitation program with external feedback. Finally, biofeedback interventions proved its effectiveness in shifting the COP position also during functional tasks like single-limb static balance, step downs, lateral hops, and forward lunges. All articles agreed to conclude that, even if further research on the medium and long-term effects of biofeedback is needed, biofeedback should be part of the interventions for CAI rehabilitation as it resulted in significant clinical improvements.

3.2 Biofeedback impact on plantar pressure measures

L. Donovan et al. (29) were the first who in 2016 performed a laboratory study aiming to investigate the effects of an auditory biofeedback device in individuals with chronic ankle instability. They hypothesized that the altered gait pattern characterized by increased lateral loading and increased contact time of the lateral column of the foot during gait, as well as the impaired peroneus longus activation during the gait cycle were contributing factors to the high recurrence of ankle sprain frequently associated with CAI condition. Given the necessity to address rehabilitation interventions to modifying gait kinetics and kinematics and the evidence that gait training with external feedback has already been demonstrated useful to correct abnormal movements at hip and at knee level (38), they performed a study regarding the effect of gait retraining using external feedback on plantar pressure measure and muscle activation in people with CAI. In particular, they adopted an auditory biofeedback device that elicited a noise when the pressure under the head of the fifth metatarsal exceeded the threshold, inducing patients to modify their gait pattern. The device was designed for decrease the lateral foot pressure in response to the auditory biofeedback and increase peroneus longus and gluteus medius muscles activation prior to initial contact and throughout the stance phase of gait. The intervention consists of a single training session. For the baseline assessment patients were required to walk on a treadmill at their normal speed and once they felt they were walking comfortably 30s of plantar pressure and sEMG data (sEMG amplitudes for the anterior tibialis, peroneus longus, medial gastrocnemius, and gluteus medius) were collected. Successively, the auditory device was placed in the shoe of the involved limb and when the threshold was set, patients were required to walk following the instruction "to walk in a manner that is similar to their normal walking pattern, but trying to make it so the device no longer makes a noise". Once patients started walking comfortably, plantar pressure (using Pedar-X system) and sEMG data were collected for 30 s. Regarding plantar pressure measures, the results showed a diminished peak pressure of the lateral midfoot, lateral forefoot and central forefoot, and an increased pressure on the great toe during the auditory feedback condition (Fig.13). In addition, during the biofeedback condition there was a reduction in lateral midfoot and lateral forefoot pressure time integral and an increase in the region of the hallux.

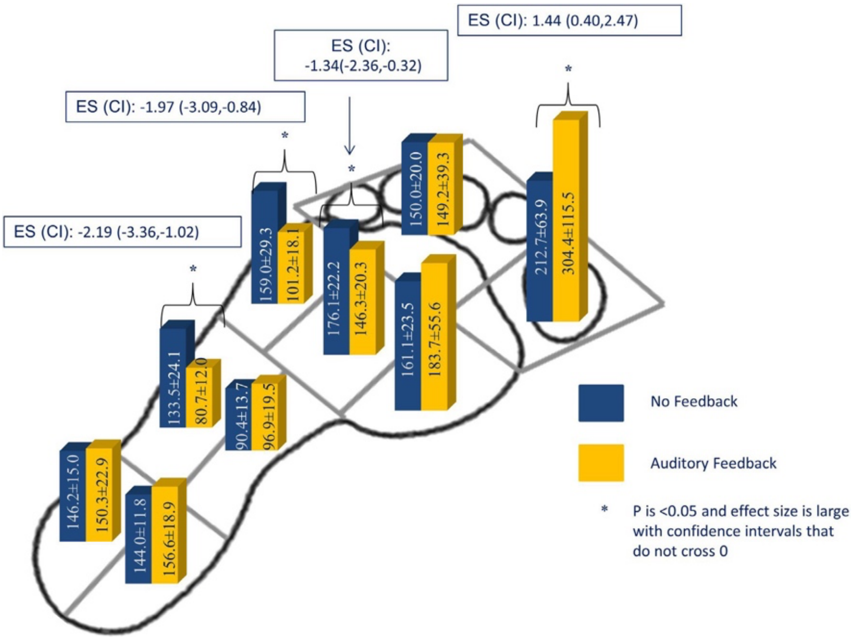


Figure 13: Means and standard deviations of peak pressure (kPa) of the nine regions of the foot during treadmill walking during no feedback and auditory feedback conditions (29)

In the auditory feedback condition time to peak pressure was reduced in the lateral midfoot as well as the contact area in the lateral midfoot. There were no differences in contact time between baseline and biofeedback conditions. Surface electromyography amplitudes showed no difference from baseline to biofeedback conditions at pre-initial contact while at post-initial contact (200 ms) when comparing conditions, there were significant increases in peroneus longus and medial gastrocnemius amplitudes during the auditory biofeedback training.

Similar results, especially for plantar pressure measures, were obtained also by D.M. Torp et al.(21). In 2019 they have demonstrated that gait retraining with a visual biofeedback tool is able to modify the pressure distribution on the sole of the foot causing a decrease of the peak pressure in the lateral column of the foot. As in the previous study, data were collected as real-time effects of a single session of gait retraining with external feedback that consisted of walking on a treadmill at self-selected pace, but in contrast, the external feedback was provided by a visual feedback tool. The device consisted of a laser pointer that projected a cross-line was projected by the laser on to the wall in front of the treadmill. Successively, a strip of tape was attached to the wall following the vertical line projected by the laser so that the neutral position of the foot was tracked. Participants were instructed to 1) walk in a manner in which the vertical laser line aligns with the piece of tape on the wall; 2) the laser should only move up and down the piece of tape so try to walk in a manner in which the laser cross does not move left, right or rotate; 3) try to walk as normally as possible while adhering to these instructions. After an acclimation period to the instructions, data were collected for 30 sec using an in-shoe plantar pressure system. The results showed that during the external feedback condition there was a reduction in peak pressure at lateral midfoot, central forefoot and lateral forefoot, and a decreased pressure time integral at the lateral heel and lateral midfoot. An increase at the toe region of both peak pressure and pressure time integral was recorded in the feedback condition. No significant difference in contact time were registered between the two conditions. Lastly, the cop gait line shifted medially during the first 80% of stance.

3.2.1 Altered motor control in people with CAI

The mechanism underlying the results obtained in those three studies could be explained by a modification of the muscular activation during gait cycle. Donovan et al.(29) investigated the muscular activity during gait in the baseline condition and biofeedback condition with a surface electromyography. It turned out that in the auditory feedback condition there were no differences in pre-initial contact amplitudes for the anterior tibialis, peroneus longus, medial gastrocnemius, or gluteus medius while sEMG amplitudes of the medial gastrocnemius and the peroneus longus phase increased significantly at post-initial contact. It has been demonstrated by M.A. Feger et al.(39) that CAI people have a characteristic motor-control pattern during gait. Compared to healthy control group, CAI group showed an earlier time of activation relative to initial contact for the anterior tibialis, peroneus longus, rectus femoris, biceps femoris, and gluteus medius. The peroneus longus was also activated for a longer duration throughout the stride cycle in the CAI group than in the control group. It is generally thought that the pre-activation of the peroneus longus is a compensation strategy that aim to repristinate ankle position on the ankle frontal plane, protecting the ankle against inversion moments. Delahunt et al. (37) called this mechanism “feed-forward mechanism” and suggest that correcting the ankle position in preparation for initial contact, the feed-forward mechanism has an important role in injury prevention. If on the one hand this characteristic pattern of motor control is able to almost repristinate a neutral position of the foot at initial contact, on the other hand it has also negative consequences as it compromises the ability of the peroneus longus to provide lateral dynamic stability to the ankle. In healthy people the peroneus longus doesn't activate until the midstance phase when it exerts a plantar-flexion force at the ankle and pulls down the first ray, assisting in pronation and subsequently stabilizing the first ray as a rigid lever for propulsion(39). If the muscle is already contracted at initial contact, as it happens in CAI condition, the peroneus longus is incapable of successfully react to inversion perturbations because of a decrease in the sensitivity of the muscle spindles during active concentric muscle contractions. That means that the pre-activation of the peroneus longus functions as a compensatory strategy to improve foot positioning at initial contact but decrease the ability of the peroneus longus in assuring lateral dynamic stability of the ankle through its pronation role while weight bearing. As a consequence, the peroneus muscle isn't effective in ankle stabilization especially in case of unexpected destabilizations predisposing CAI people to sustain recurrent sprains and feelings of instability.

The study of R.M. Koldenhoven et al. (2016) aimed to verify if gait training with visual external feedback can improve gait mechanics and especially can reduce ankle inversion during walking in order to decrease the risk of subsequent lateral ankle sprains for individuals with CAI. The intervention consisted of a 4-week rehabilitation program in which participants were randomly assigned to the gait biofeedback group or to the control group. The visual biofeedback device projected the ankle inversion angle at initial contact as an oval onto a screen in front of the treadmill. A maximum threshold for ankle inversion was set and when ankle inversion exceeded it the oval onto the screen became red. The threshold was progressively decreased each session trying to decrease the ankle inversion angle by up to 100% which would reflect a neutral foot position at initial contact. Participants received biofeedback for respectively 8, 12, 16, and 20 minutes the first four session and then biofeedback was decreased by 4 minutes per session during the last four session. Results showed that at the follow-up time point (24-72 hours after completion of the last rehabilitation session) there were significant improvements in the position of the foot at initial contact for the group which trained with visual feedback. The biofeedback group, in fact, reduced their ankle inversion ankle at initial contact and throughout the entire stride cycle. Nevertheless, this improvement is associated to an enhancement of that feed-forward mechanism in which the peroneus longus activates during swing phase. Such compensation strategy, as was said before, may be able to correct the inverted positioning of the foot but reduced the ability of the peroneus longus to stabilize the ankle during the stance phase.

3.3 Retention of biomechanics improvements

Although up to this point interventions with external biofeedback in CAI rehabilitation seem to bring significant benefits, is it true that both the studies of L. Donovan et al. (2016) (29) and D.M. Torp et al. (2019) (21) had not investigated whether improvements showed during gait re-training were retained as soon as the feedback tool was turned off or, what is most important, if retention was present also several days after the gait re-training. In this regard, the study(26) conducted by K.G. Migel and E.A. Wikstrom in 2021 assessed biofeedback effects on center of pressure immediately after the conclusion of the gait re-training, while the 2022 study by Danielle M. Torp et al.(34) verify if there were retention effects seven days after a gait re-training multisession program.

K.G. Migel and E.A. Wikstrom (26) studied the impact on COP location of a single training session of gait re-training with haptic biofeedback, evaluating its effect just after the end of the training (immediate post-test evaluation) and after 5 minutes. Gait re-training with external feedback was performed in two different conditions: in a laboratory where participants walked on a treadmill for 10 minutes or in a "real-world condition" where participants walked on a brick sidewalk for one mile loop. The haptic tool consists of a small force sensing resistor (FSR) which was placed in the shoe under the fifth metatarsal head, a vibration motor which was attached on the lateral malleolus with some elastic strap and the electronics and the battery that were secured on the top of the shoe of the involved limb. The device was calibrated for each patient so that when the FSR detected pressure under the lateral foot that exceeded the individualized threshold, the vibration motor turned on and provided a vibration stimulus. The only instruction that was given to participants was to "walk so you do not get the vibration". After baseline assessment without feedback, participants were randomly assigned to one of the two environment conditions and performed the other after 48h. Data were collected at immediate post-test and after 5 minutes. Results showed that vibration gait re-training had created clinically meaningful changes to COP location in both the laboratory and real-world condition at immediate post-test evaluation and that those improvements were retained after 5 minutes. In the lab condition COP location was more medial from initial contact to terminal stance/pre swing (phase 1 to phase 9 of gait cycle according to the classification adopted by the authors) at immediate post-test evaluation and from early midstance to terminal stance/pre swing (from phase 2 to 9). In the real-world training, data collection revealed that COP location was more medial from initial contact to terminal stance (indicated as phases 1–7) at immediate post-test relative to baseline, and from initial contact (phase 1) to late midstance (phase 6) at retention evaluation. Even if the results demonstrate that improvements in COP location were retained, a period of 5 minutes appears too short to clearly affirm that biofeedback interventions produce significant effects on the medium-long term.

In the study conducted by D.M. Torp et al. in 2022 (34) participants performed 8-sessions of 30-minute treadmill walking over 2 weeks with auditory biofeedback. Data on biomechanics and talar cartilage characteristics were collected at immediate post, that was 24-48h after the final intervention, and then at 1-week post, after 7 days from the final training session. The decision of capturing data collections when the intervention was already finished with the auditory biofeedback turned off and after seven days from the conclusion of the rehabilitation program, allowed the authors to assess the effectiveness of gait re-training, evaluating if there were any effects' retention. The hypothesis tested was that the auditory biofeedback group would significantly reduce lateral plantar pressures and shift center of pressure medially and reduce talar cartilage deformation patterns, compared to the control group. The intervention session consists of 30 minutes of walking on a treadmill with an auditory biofeedback. Once the auditory feedback tool was individually calibrated patients were told to "walk in a manner where you do not hear a noise, but that is still as natural and comfortable as possible". Plantar pressure measures were collected using a Pedar-X pressure in-shoe insoles while ultrasound collected data about talar cartilage. Results fully confirm the authors' hypothesis: at immediate post evaluation there was a reduction of peak pressure in the lateral midfoot and lateral forefoot, while peak pressure increased in the medial forefoot. The reduced peak pressure was then retained also at 1-week post evaluation. Similarly, the maximum force was reduced in the lateral midfoot and lateral forefoot at immediate post evaluation and at 1-week post. The maximum force increased at medial forefoot both at immediate post and 1-week post assessment. In addition, at immediate post evaluation there was a medially shift of the center of pressure between 45% and 95% of stance. This improvement in center of pressure was observed also seven days after the conclusion of the training program when the center of pressure location was measured and was find out that its medial shift was retained between 35% and 45% and at 85% of stance phase. Results concerning cartilage health will be discussed later.

This study not only is the first which demonstrated a significant retention of the results obtained, but it also followed a multisession program of gait re-training instead of a single training session as we find in previous articles. The choice of extending gait re-training from a single intervention to a multiple session program that take place over two weeks may be due to the encouraging findings of the previous studies about the use of a biofeedback tool in CAI population. Following a more articulated program has several advantages. First, it allows to overcome a major limit of those studies that attained a single session without any follow-up that consists in the impossibility to speculate on the effect of biofeedback training in absence of the feedback and even more in the medium-long term. Moreover, a multiple training program, thanks to its longer duration, have an impact also to patients' feeling and beliefs about their condition that can be evaluated through the PRO's scales (Patient Reported Outcomes scales). This is an important aspect of CAI people rehabilitation because ankle instability is a chronic condition and evidence has strictly demonstrated an association between the development of CAI and a decrease in physical activity participation and a generally diminished ankle function.

3.4 Patient-reported outcome in CAI population

The study of R.M. Koldenhoven et al. (2016) (33) analyzed the effects of visual gait biofeedback (GBF) and impairment-based rehabilitation on gait biomechanics and patient-reported outcomes (PROs) in individuals with chronic ankle instability (CAI). Participants, divided into a biofeedback group and a control group, attained a rehabilitation program that consisted of 8-session taking place over four weeks of gait retraining using visual external feedback. Prior to participation at rehabilitation program and at its conclusion, participants completed the following questionnaires to provide an assessment of how they perceived their ankle function and physical activity: Foot and Ankle Ability Measure-Activities of Daily Living (FAAM-ADL), FAAM-Sport Scale, Identification of Functional Ankle Instability (IdFAI), Tampa Scale of Kinesiophobia (TSK), International Physical Activity Questionnaire (IPAQ), and the Patient Specific Functional Scale (PSFS). The Global Rating of Change (GROC) and PSFS questionnaires were administered at the half-way (beginning of session 5/8) and at follow-up visit to provide an assessment of how our participant's perceived improvements or lack of improvements in ankle function during and after rehabilitation. At the conclusion of the 4-week program, the questionnaires were completed again by participants of both the biofeedback group and control group. The biofeedback group showed improvements for FAAM-ADL, TSK, and GROC than the control group. For the FAAM-ADL, even if the improvement wasn't statistically significant, the biofeedback group showed a 9.3% increase, whereas the non-biofeedback group improved only by 6.4%. For the FAAM-sport, instead, both groups improved by 15% and the GBF group score improved enough to exceed the cut-off score to be classified as having CAI (according to the study inclusion criteria <85% for FAAM-sport). For the GROC, the biofeedback group reported an improvement of 3.5 points at the half-way time point and 5.5 points at follow-up while the control group only had an improvement of 2.3 points at the half-way time point and 3.9 points at follow-up. TSK scores following rehabilitation showed that biofeedback group are more likely to have a decrease of 6 points or more on the TSK compared to the control group.

These findings have a great relevance since only in the last decade research on CAI has started to take into account those sensory-perceptual impairments such as kinesiophobia, self-reported function, perceived instability and diminished health-related quality of life associated with CAI. In the 1960's, the first studies(40)(41) on CAI focused on mechanical and functional deficits associated with chronic ankle instability condition aiming to further understand the causes contributing to the development of CAI. Originally, mechanical instability and functional instability were considered the two main factors that lead to CAI condition. In 2002, Hertel et al.(17) proposed an updated model describing the potential mechanical and functional (sensorimotor) contributions to CAI. Mechanical insufficiencies in the model included pathologic laxity, arthrokinematics restrictions, degenerative changes, and synovial changes, whereas functional insufficiencies included impairments in proprioception, neuromuscular control, strength, and postural control. However, nowadays the dichotomy mechanical-functional impairments appears to be insufficient to describe the causes of CAI. The advent of the biopsychosocial model shifted the attention to areas such as self-reported function, health-related quality of life, kinesiophobia, altered movement patterns, and physical activity levels. Thus, research which has traditionally focused on the pathophysiology of this condition from a disease-oriented perspective, has started to include the patients' perception of their health status, to better understand if and in what manner CAI impacts on individuals' life. These changes have led to the development of several patient-reported outcomes to measure functional limitations in patients with CAI, including specific scales like Ankle Joint Functional Assessment Tool (AJFAT), Foot and Ankle Ability Measure (FAAM), Foot and Ankle Disability Index (FADI) and Chronic Ankle Instability Scale. A study conducted by Eechaute et al. (42) assessed four different patient reported outcomes scales and concluded that the most appropriate to evaluate and quantify functional limitation in CAI population were the Foot and Ankle Ability Measure (FAAM) and Foot and Ankle Disability Index (FADI). In addition to these kinds of evaluative region-specific instruments, researchers have used also more generic instruments like generic and dimension-specific instruments to measure health-related quality of life (HRQOL). M.N. Houston et al.(43) published in 2015 a comprehensive systematic literature review of the health-related quality-of-life (HRQOL) differences among individuals with chronic ankle instability (CAI), ankle-sprain copers, and healthy control participants. They have divided studies by the between-groups comparison (CAI and ankle-sprain copers, CAI and heath participants, ankle-sprain copers and healthy control participants) and the type of instrument adopted to measure the quality of life: generic instruments, region specific instruments and dimension specific instruments. Generic outcomes are not specific to body region or condition and are designed to assess the patient's overall health (eg, Short Form-36 [SF-36]). Region-specific outcomes (eg, FAAM and FADI) are specific to a joint or region of the body, and dimension-specific outcomes (eg, Tampa Scale of Kinesiophobia [TSK-17]) are specific to a disease or health dimension, such as fear of reinjury. Their findings revealed that for generic instruments there is moderate evidence that individuals with CAI experience HRQOL deficits compared with healthy control participants. For region-specific instruments, instead, they found moderate to strong evidence to suggest that individuals with CAI reported lower region-specific outcomes than did healthy control participants and ankle-sprain copers. The scales adopted for measure foot and ankle region disability were the FAAM, FADI, CAIT and AJFAT. Given the strong difference observed between the CAI and healthy control group, the study suggest that such measures should continue to be used in research and clinical practice to describe functional limitations in individuals with CAI. Lastly, there was limited evidence about dimension-specific instruments but the study of Houston et al(43) which compared the fear of reinjury using the Fear-Avoidance Beliefs Questionnaire and the TSK-11 between CAI and healthy participants, has found a heightened fear of reinjury of the CAI group compared to the healthy control participants.

To sum up current evidence about CAI population's quality of life, it is possible to say that there is evidence for a decreased healthy related quality of life in people with CAI, particularly when it is measured using region-specific outcomes rather than generic instruments. In addition to this, a relation between chronic ankle instability condition and an increased fear of movements and diminished participation in physical activities and sport has been reported.

The importance of patients' perspective in CAI condition has been recognized also by the International Ankle Consortium. The International Ankle Consortium is an international community of researchers and clinicians who promote research-informed knowledge related to pathologies of the ankle complex. In 2016 it published a "position statement"(44) in which selection criteria for patients with chronic ankle instability were defined (Table 2). The inclusion criteria consist in three mainly points. The first one is an history of at least one significant ankle sprain, and thus, is referred to an injury that really happened. The second inclusion criterion, instead, talks about a history of the previously injured ankle joint to "giving away" and "feelings of instability". The giving away is described as the regular occurrence of uncontrolled and unpredictable episodes of excessive inversion of the rear foot, but it doesn't result in an acute ankle sprain. Not causing an acute injury, the giving away sensation can only be referred by patients. Similarly, the feeling of ankle joint instability is defined as the situation whereby during activities of daily living and sporting activities, the subject feels that the ankle joint is unstable and is usually associated with the fear of sustaining an acute ligament sprain. To evaluate and confirm self-reported ankle instability, the International Ankle Consortium suggest some recommended ankle instability-specific questionnaires such as Ankle Instability Instrument (AII), Cumberland Ankle Instability Tool (CAIT) and Identification of Functional Ankle Instability (IDAFI). Moreover, the Foot and Ankle Ability Measure (FAAM) and Foot and Ankle Outcome Score are mentioned in the third inclusion criterium as they are recommended to describe the level of disability and self-reported function of CAI people. In conclusion, the International Ankle Consortium has recognize the relevance of patients' perspective to identify chronic ankle instability condition and additionally it promotes the use of patient-reported outcome questionnaires to evaluate self-reported function and assess the level of disability showed by CAI population.

3.5 Biofeedback interventions’ role in osteoarthritis prevention

Another aspect of CAI that is often underestimated, is its correlation with post-traumatic osteoarthritis. It has been demonstrated that chronic ankle instability is a risk factor for the development of post-traumatic osteoarthritis (PTOA) as long-term consequence(45). K. D. Harrington have estimated that 78% of people with CAI develop PTOA within 10 years of their initial ankle sprain(46). Since the advent of osteoarthritis is thought to be connected to the altered biomechanics of those with CAI and specifically to the lateral shift of the plantar pressure and of the center-of-pressure, it is reasonable to investigate if repristinating a more medial plantar pressure distribution, biofeedback interventions are an effective strategy in PTOA prevention. Danielle M. Torp et al.(34) studied in 2022 the effects of gait training with external feedback on biomechanics but also on talar cartilage characteristics in individuals with CAI. Ultrasonography captured talar cartilage thickness and echo intensity in three regions (total medial, lateral) of the foot before and after 8-intervention sessions of gait training. At baseline assessment participants were required to lie seated for 30 minutes to unload the talar cartilage and then ultrasound data were collected. The ultrasound was repeated during immediate-post and 1-week-post assessment. Hypoechoic cartilage indicates adequate water content and healthy articular cartilage while hyperechoic areas within the cartilage indicates reduced proteins and water molecules, potentially representing a decline in cartilage health. Results didn’t show any significant difference in cartilage characteristics between baseline and follow up assessment. One of the possible reasons for explaining the absence of meaningful changes is that a rehabilitation program of just 2 weeks isn’t enough to produce observable modifications in cartilage pattern. However, a study conducted by Jaeho Jang et al. in 2021 (26) investigated the impact of gait training with external haptic feedback on vertical ground reaction force and ankle joint contact forces (JCF) after a single training session. Ten participants underwent a single gait training session with haptic feedback. The biofeedback tool was the same described previously made of a force sensing restor, vibration motor, battery, and electronics. Participants walked on a treadmill for 10 minutes. Data was captured during an early (minute 1 to 2) and late (minute 9 to 10) adaptation period. At the early adaptation the propulsive peak vGRF, time to propulsive peak, and propulsive loading rate were significantly reduced compared to baseline. Propulsive peak vGRF and time to propulsive peak remained reduced also at the late adaptation assessment. In addition, among JCF variables, ankle peak and impulse JCF were significantly reduced compared to baseline at the early adaptation period and ankle impulse JCF remained reduced at the late adaptation period compared to baseline. Overall, results demonstrate that vibration feedback intervention can modify vGRF and JCF variables which are thought to influence cartilage compression and degeneration over time. Therefore, this study provides additional support for the use of a vibration feedback gait retraining strategy and make possible to hypothesize that a more structured rehabilitation program prolonged in time could have positive effects on the prevention of post-traumatic osteoarthritis.

3.6 Integrating the Dynamic System Theory in CAI rehabilitation

Up to this point, adopting external feedback during gait re-training has been demonstrated to improve CAI people condition. However, gait re-training with external biofeedback in a laboratory context could be somehow different from walking outside. In fact, in the majority of cases gait re-training is performed in a gym on a treadmill. The advantages of walking on a treadmill lie in the fact that the gym is a controlled and safe environment, where the subject walk generally supervised by a therapist. In addition, the treadmill offers a smooth surface free from irregularities, steps or obstacles. The outside seems to be quite different. The surface isn’t always as regular as the inside, it might be inclined or uneven or slippery for instance in case of rain. The predictability of the gym context is replaced by unpredictable events and an infinite variability of situations that forces individuals to direct their focus on the outside rather than on their movement pattern. For these reasons, gait re-training which requires some specific instrumentations, that vary depending on the type of biofeedback, and in most cases is performed on a treadmill in a laboratory context, appears to be in contrast with the assumption that rehabilitation environment and the movement goal should emulate a functional movement and a real context in which it would be performed to optimize motor learning. Recent developments in motor control principles suggest that as any functional daily task explicitly requires an interaction between the neuromuscular system and the environment, effective motor training should incorporate movement components and an environment that resemble the targeted task in the relevant functional context(28). However, it is not true that gait re-training using a biofeedback tool must be performed in laboratory context. K.G. Migel and E.A. Wikstrom (2021)(26) studied the effect of laboratory and real-world gait re-training with vibration feedback on center of pressure during gait in people with chronic ankle instability. They already knew thanks to previous studies that gait re-training using auditory or visual external feedback techniques was effective in reducing plantar pressure under the lateral foot, shifting the center of pressure more medially (29),(21) and improving frontal plane ankle position(33). However, since the effectiveness of use of an external biofeedback during gait retraining in a real-world context had not been proven yet, the purpose of their study was to compare the impact of laboratory and RW gait retraining with vibration feedback on the COP location during walking in people with CAI. Their hypothesis was that, given that variability is known to improve motor learning, real-world training could enhance motor learning due to the inherent variability encountered through uneven surfaces and unexpected perturbations in an uncontrolled environment. The intervention consists of both laboratory training session and real-world training session. In the first case participants walked for 10 minutes on a treadmill with vibration feedback, whereas during real-world training participants walked a supervised, one mile loop on a brick sidewalk with vibration feedback. The results of their investigation fully confirmed their prior hypothesis. Laboratory gait retraining has been successful in shifting the center of pressure location from a more lateral position to a more medial one, reinforcing the previous studies that have demonstrated the effectiveness of gait retraining with an external biofeedback. The real-world training also has showed positive results. The COP location of participants who attained the real-world training, in fact, shifted medially from initial contact through part of terminal stance at the immediate post-test assessment and the change was retained from initial contact to late midstance at the 5-minute post-test evaluation. Even if the study design included a single training session, the results have demonstrated that an outside training session with vibration feedback can create immediate COP location changes for the first 70 % of stance phase during walking and that the medial shift in COP location is retained in the short terms.

Starting with gait re-training with external feedback in a laboratory-controlled context and successively continuing gait retraining outside could be a good strategy to improve the task difficulty.

According to the dynamic system theory(47), a systematic progression through the exercises and proposals is the most important element for the development of functional variability. The dynamic system theory tries to explain how the sensorimotor system develops different strategies to accomplish a movement goal. The sensorimotor system is the result of the interaction of three different areas: the health of the subject (organismic constraint), the task to perform (task constraint) and the environment in which the movement is executed (environmental constraint) (Fig.15).

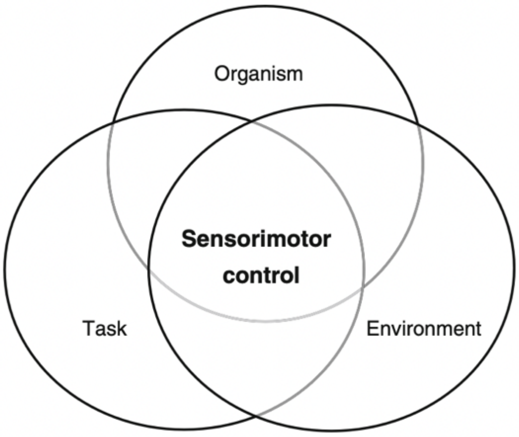


Figure 15: Sensorimotor organization based on the interaction of organismic, task, and environmental constraints as described by the Dynamic Systems Theory (47)

A healthy sensorimotor system is able to accomplish movement and cope with changing task and context thanks to its ability to collect information from itself and from the environment and put them in correlation, considering also the task goal. However, when an injury like an acute lateral ankle sprain occurs the organismic constraints increase and the sensorimotor system has to find out other strategies to accomplish a movement goal. This is what happens in those with chronic ankle instability, whose sensorimotor system has remained impaired after a first ankle sprain. The musculoskeletal injury in fact, causes alterations in sensorimotor control that leads to a decreased in functional activity which results in a lower participation in sport and physical activities. According to the theory, the organismic constraint can be overcome by improving functional variability. In other words, rehabilitation should aim to improve the ability of the sensorimotor system to successfully cope with changing task and environmental constraints to accomplish movement goals(47). This can be reached by the development of a systematic progression through the requests so that changing demands challenge the sensorimotor system to find new movement solutions. During rehabilitation both the task and the environment constraints can be modify. The therapist can ask to the patient progressively more difficult tasks or can modify the environment from a predictable to more unpredictable context. Walking outside is a great example of environment constraint. However, it is also possible to increase the difficulty of the task from gait training to other functional tasks. The dynamic system theory suggests that when a movement goal is performed error free, the complexity of the request should be increased. Therefore, translating it to gait re-training with external feedback, when a patient manages to walk almost without exceeding the threshold and producing the feedback cues, the task complexity might be increased.

Danielle M. Torp et al. (2021) (30) has studied the impact on biomechanics of two biofeedback tools in CAI population while performing functional tasks. The authors' purpose was to determine the effects on COP location of visual and auditory external feedbacks during four different tasks: single-leg static balance, step down, lateral hops and forward lunges. Overall, both forms of external feedback appeared to successfully modify ankle biomechanics during functional tasks. Actually, each form of external biofeedback had a unique effect on each task. During the eyes-open static balance performance both the visual and auditory feedbacks caused a shift of the center of pressure from the anterolateral foot quadrant to the posteromedial foot quadrant. The auditory biofeedback had the same effect also during the eye-closed static balance trials (Fig.16).

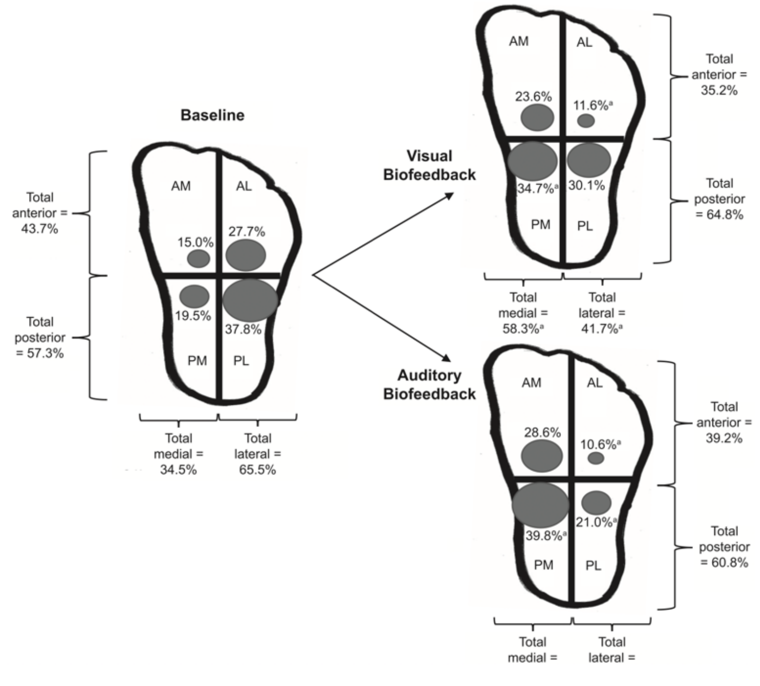


Figure 16: Percentage of pressure data points in each quadrant during the eyes-open static balance trial in the baseline and visual- and auditory-biofeedback conditions (30)

During step down in the auditory biofeedback condition, there was an increase in lateral heel peek pressure and pressure-time integral, whereas there was a reduction of the pressure-time integral of the lateral forefoot. During lateral hops, in the visual biofeedback there was an increase in peak pressure and pressure time integral in the lateral heel region and the lateral midfoot region. The auditory biofeedback, instead, didn't produce significant changes in plantar pressure distribution. During forward lunges, the auditory biofeedback condition decreased the pressure-time integral in the lateral forefoot while no significant differences were observed between the visual feedback condition and baseline condition. On average, both external biofeedback had positive effects on static balance, while their efficacy differed among the four functional tasks. When performing the step down and forward lunge, participants were more responsive to auditory biofeedback, whereas during the lateral hop, they were more responsive to visual biofeedback.

The importance of this study is double. On one hand being the first study to use a biofeedback strategy during functional activities, it demonstrates that biofeedback interventions are not bound to gait training but can be applied to a progression of the rehabilitation proposal from a simpler to more complex tasks, up to functional and sport-related activities. On the other hand, comparing visual and auditory biofeedback, it poses the question about what biofeedback type give the best results.

3.7 Comparison between different types of feedback

Evidence agrees that augmented feedback is a valid instrument to facilitate motor learning.(48)(31)(49). Feedback in fact, giving to patients information related to how a movement has been executed and what are the effects of that movement, has a role of information provider to the learner. The "guidance hypothesis" proposed by Salmoni et al. (50) clearly addressed the informational role of feedback. The basic principle of the guidance idea is that the information provided by feedback guides the learner to the correct movement pattern, facilitating performance during practice. Studies by Shea and Wulf (1999)(51) and Wulf et al., (2002)(52) show that feedback inducing an external relative to an internal focus of attention resulted in more effective learning. Evidence affirms that adopting an internal focus and thus directing attention to one's body parts or movements results in conscious control attempts that constrain the motor system and disrupts automaticity(53). When performers consciously try to control their movements thereby interfering with automatic control processes, the performance is disrupted. Furthermore, Wulf and Lewthwaite (2010)(54) argued that, by referring to the performer's body movements, internal focus instructions or feedback may promote a focus on the self, leading to concerns and worries about one's performance. Finally, self-construct has increasingly been recognized as an important factor within social environments, influencing individuals' thoughts, actions, and behavior, often implicitly. The fact that motor performance often takes place in the presence of others and can be evaluated by them, may in and of itself lead to a state of selfconsciousness and subsequent self-evaluation. This, in turn, can lead to “micro-choking” episodes.(54) On the other hand, the advantages of adopting an external focus, relative to an internal focus, have been explained with increased automaticity in movement control(53). Moreover, literature advocates that external feedback is more beneficial as it produces longer lasting improvements in motor function. When a skill was learned through external feedback there were greater retention and transfer skills. (49) While the superiority of external rather than internal focus of attention in enhancing motor learning has been strongly demonstrated, there are still many doubts related to what external feedback modality produces the best results and the frequency with which feedback should be presented. Augmented feedback can be provided through different modalities: visual feedback, auditory, haptic feedback or a combination of them. Affirming that one modality is better than another is problematic for the following main reasons. Firstly, each modality includes a variety of types of feedback which make difficult to generalize the effects of the whole category. For instance, many possibilities exist for visual feedback ranging from abstract visualizations, such as bars, lines or numbers, to less abstract or “natural visualization” such as 3-D animations.

Moreover, the effectiveness of a feedback strategy in enhancing motor learning depends on multiple factors such as the point in time at which feedback is provided, the frequency of exposition to the feedback and the difficulty of the task. Feedback can be provided either during motor task execution (concurrent or real-time feedback) or after it (terminal feedback) and with an high frequency (100%, after every trial) or with a reduced frequency.(48) Finally the complexity of the task required influences feedback’s effectiveness.(31) Literature has proven that visual feedback is more effective for simple tasks rather than complex ones(31), this characteristic makes it suitable for gait retraining proposal but not for more complex tasks such as functional tasks. In addition to this, visual feedback requires a screen or a wall where to projecting images, and for this reason this modality is bounded to a laboratory context. However, visual feedback assures to patients a continuous exposure to feedback which is associated to enhanced motor learning and retention. If this is true for visual feedback, auditory and vibration feedback expose patients to a reduced frequency as the noise or the vibration stimulus is elicited only when plantar pressure exceeds the threshold, signaling the error. Moreover, producing a cue only when plantar pressure overcomes the set threshold, vibration and auditory feedback point out to patients only the presence of an error but they don’t give information about the quality of the error.(31) However, the advantage of vibration feedback compared to the auditory one is that it can be used in different context (i.e. outside) while auditory feedback needs a quiet environment to hear the cues. In conclusion, as literature doesn’t provide answers on what king of biofeedback is the best, the choice of biofeedback should be made on the basis of the aim to reach, the complexity of the task, the context where tasks will be performed and lastly on the available instrumentation. In this regard, other authors(25)(55) conducted similar studies to those included in this work, investigating the effect of gait training on plantar pressure measures, COP gait line and muscle activity in CAI population. However, they didn't utilize a biofeedback, but a gait training device (Fig. 17) made up of located tracks positioned between the participant's legs and elastic bands. Participants stood on the treadmill with feet shoulder width apart, elastic bands were stretched to approximately 150% of their resting length and tied around the shank so that they applied a medially directed force. Next, they start walking and plantar pressure measures as well as sEMG amplitudes of anterior tibialis, peroneus longus, medial gastrocnemius, and gluteus medius were collected. Similarly, to the studies on biofeedback interventions, they obtained a reduction of peak pressure and pressure time integral in the lateral aspect of the foot which instead increased in the medial aspect of the foot and on the hallux. During the stance phase, the center of pressure was shifted significantly medially, and the lateral midfoot contact area was reduced. Lastly, the peroneus longus activation increased during the 200ms prior to and the 200ms following initial contact. These findings demonstrate that elastic bands are effective in decrease plantar pressure on the lateral column of the foot and represent a possible strategy to treat gait impairment in those with CAI. However, even if elastic bands give to patients a sort of haptic feedback, those studies weren't included in this work as they didn't meet inclusion criterium which referred to biofeedback interventions.

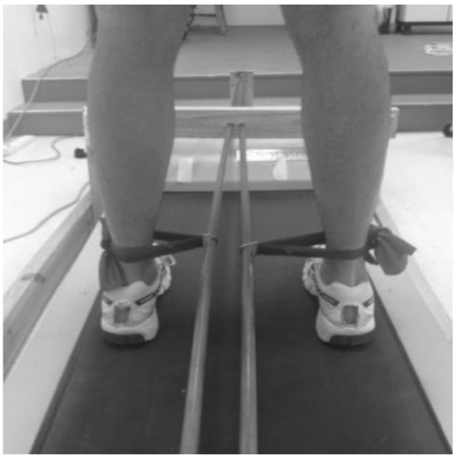


Figure 17: Gait training device with elastic bands (25)

In conclusion, recent research has been conducted on multimodal feedback strategy (i.e. audio-visual feedback) demonstrating its effectiveness in accelerating motor learning.(31) Further studies are needed, but multimodal feedback might be the future for rehabilitation.

3.8 Limitations

The main limitation of these studies is related to the shortness of the intervention (several studies performed a single training session) and the post-test data collection which were mostly collected as real-time effects or at immediate post. For these reasons it is not possible to speculate on the long-term effects of biofeedback interventions in chronic ankle instability.

Another limitation consists of the choice of not to include the contralateral limb within study's analysis. Evaluating the controlateral limb would make possible to compare the improvement of the involved limb related to the patient's other leg instead of to generic data on healthy population, and thus respect the individuality of each participant.

Next, other limitations are related to biofeedback devices. As was said before, literature on biofeedback and their effectiveness is lacky, so that we are still unable to compare different types of biofeedback and no conclusion can be drawn on what allows to reach the best results. In addition, the characteristics and functioning of biofeedback depend on what company produced them. This can be a problem, for instance, in the calibration on the device which can function differently from a device to another. In this regard, not all articles provided a detailed description of the device calibration procedure which might make it more difficult for other authors to replicate their study.

4 CONCLUSION

Chronic ankle instability (CAI) is a condition characterized by recurrent ankle sprains or perceived instability of the ankle that persists for more than 12 months after an initial injury and results in activity limitation and participation restriction. Current rehabilitation approaches have been reported to be unable to modify the altered ankle biomechanics and impaired peronei muscles activity showed by people with CAI. The inverted position of the foot at initial contact and the laterally shifted center of pressure during weight-bearing are thought to place the foot in a position predisposing to ankle sprain injury or bouts of instability. Moreover, the altered biomechanics is responsible for an increased risk for the development of post-traumatic ankle osteoarthritis.

The hypothesis underlying biofeedback interventions is that thanks to the external feedback individuals with CAI become aware of their foot positioning at ground contact and may manage to restore proper biomechanics. This hypothesis has been confirmed by all the studies which after biofeedback interventions found a medial shift of the center of pressure, a less inverted position of the foot at initial contact, reduced vertical ground reaction forces and joint contact forces. These findings suggest that biofeedback strategies are successfully in improving biomechanics alterations in those with CAI and thus may be able to reduce the risk of recurrent ankle sprain. In addition, biofeedback interventions resulted also in significant improvements in patient-reported outcomes (PRO's). While in the past literature related to chronic ankle instability has focused mainly on functional and mechanical impairments associated with CAI, nowadays the relation between CAI condition and impairments like lower self-reported function, kinesiophobia and diminished level of physical activity has been well established and thus the effectiveness of biofeedback interventions to impact individuals' perception of their health status enhance the recommendation to add biofeedback interventions in CAI rehabilitation approaches.

However, we ought to consider that these results refer to the short-term effects of biofeedback interventions and, therefore, further research is needed to establish if they are retained in the long-term.

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