DETECTION AND APPROACH OF INTRINSIC RISK FACTORS FOR ACHILLES TENDINOPATHY

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Knowledge is proud that he has learned so much, wisdom is humble that he knows no more.

(William Cowper)

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CHAPTER 1

GENERAL INTRODUCTION

INTRODUCTION

The Achilles tendon is the largest and strongest tendon in the human body (40). During sport activities, tendon forces are recorded equal to 12.5 times body weight (53). Therefore, it is not surprising that the Achilles tendon injury is one of the most common tendon disorders. Brunet et al. noted that 15 - 18 % of all running injuries concern the Achilles tendon (17). Achilles tendon disorders can be both acute or chronic. However, the chronic Achilles tendon injury seems to be a significant cause of concern for both physiotherapist and patient.

The chronic Achilles tendon disorder is a condition that is most often seen among recreational male runners aged between 35 and 45 years, associated with overuse (2). Basketball, volleyball and badminton are examples of other sport activities with a high incidence of chronic Achilles tendon disorders (72). However, this injury is also seen in individuals who are not physically active (2,32).

Most patients with a chronic Achilles tendon overuse injury report an exercise – induced pain 2 to 6 cm proximal to the tendon insertion on the calcaneal bone (2). According to the classification of Blazina et al. (16), pain most often occurs at the beginning and after exercise. When the pathology progresses, pain will continue during sports activity. Finally, pain can appear at rest and during activities. Morning stiffness is also a recurrent symptom of this pathology. Moreover, Cook et al. stated hypothetically that there is a good correlation between the severity of the injury and the degree of morning stiffness (20). The degree and time of stiffness are considered to be good indicators of tendon health and recovery from injury (20).

Despite a high incidence, the exact aetiology and pain mechanism of the chronic Achilles tendon injury have not been scientifically clarified.

Definition and pain mechanism

The absence of inflammatory cells in biopsies indicates that a chronic Achilles tendon injury is a non – inflammatory degenerative process (41,48,49). For example, Alfredson et al. observed by means of a microdialysis technique no significant difference in the concentration of prostaglandine E2 between painful Achilles tendons and normal tendons (6). Histopathology of painful tendons shows degeneration, a disordered arrangement of collagen fibers, and an increase in vascularity, with a singular absence of inflammatory cells and a tendency to poor healing (7,41). On magnetic resonance imaging (MRI), this type of tendon degeneration is evident as an increased signal (45,64). On ultrasound, a fusiform expansion of the tendon and hypoechoic regions are almost always visible (73).

In this respect, the nomenclature around chronic painful tendons has changed over the last decades. Nowadays, the terms tendinitis and tendonitis should be avoided. Maffulli et al stated that the term tendinosis should be used when there are signs of degeneration on imaging (60). The term tendinopathy is used as a generic descriptor of the typical clinical conditions in and around tendons arising from overuse (50,60).

Recent research has tried to identify new theories for the pain mechanism related to the Achilles tendinopathy. The biochemical model has become appealing, as many chemical irritants and neurotransmitters may generate pain in tendinopathy. Significantly higher concentrations of glutamate have been found in tendons with tendinosis compared to normal tendons (6). Recently, the importance of glutamate as a mediator of pain in the human central nervous system has been underlined (25). Alfredson and Lorentzon found that a treatment with eccentric training resulted in a decreased tendon pain in patients with an Achilles tendinopathy. In contradiction with their expectations, the concentration of glutamate did not decrease. They concluded that the unchanged glutamate concentration could possibly be explained by a decreased sensitivity to glutamate on receptor level (3). Substance P and chondroitin sulphate may also be involved in producing pain in tendinopathy (11, 34, 57, 79).

Another hypothesis states that the presence of neovascularisation plays a key role in Achilles tendinopathy (21,70,92). In order to investigate the involvement of neovascularisation in the pain mechanism in an Achilles tendinopathy, painful tendons were injected with the sclerosing agent Polidocanol (68). Öhberg et al. found that eight out of the ten patients were satisfied with the results of the treatment. They reported a significantly reduced pain during activity and no remaining neovascularisation was seen on the colour Doppler examination. On the other hand, they stated that the neovascularisation remained in the two patients who were not satisfied. Surprisingly, the results of a recent investigation state that immediately after a sclerosing injection it is possible that the pain is decreased but the intratendinous vascularity is increased (1). The same researchers have also observed a similar increased vascularisaty in the early period after eccentric training. In the majority of the observed tendons, this increased vascularity remains during 2 – 3 weeks and then gradually decreases in the succesfully treated cases. Further research should investigate if this increased vascularity might possibly be a part of a healing response induced by treatment (1).

Function of the Achilles muscle – tendon unit

A muscle - tendon unit can fulfil different functions. Firstly, a muscle – tendon unit acts as a spring during stretch – shortening cycles or plyometrics. It is common knowledge that performance is enhanced when a concentric muscle activity is preceded by an eccentric phase in comparison to an isolated concentric contraction (13,29). Several studies claimed that this better performance is due to a greater storage and re-utilisation of series elastic energy (30). The work that is done upon the muscle during stretch can be stored in elastic structures (mainly tendons) and subsequently re - utilised during shortening, which leads to a greater performance. During almost all sport activities, the Achilles muscle – tendon unit is exposed to many stretch – shortening cylces (52). Therefore, the elasticity of the tendon plays an important role in sport performance. It is claimed in the literature that both strength and elasticity of the muscle – tendon unit should be well - adapted in order to execute these stretch – shortening cycles in an energy – saving way (30).

Secondly, in predominantly concentric contractions, a muscle - tendon unit acts as a convertor of metabolic energy into mechanical work. The force, generated by the muscle, should be transferred immediately to the bone, in order to make limb movement possible. By linking muscle to bone, a muscle – tendon unit transfers a contractile force across a joint (67). The stronger the muscle – tendon unit, the more work that could be generated during concentric contractions (30,13,87).

Therefore, during daily and sports activities, a muscle – tendon unit has to be both strong and elastic. Consequently, in the construction of prevention or rehabilitation programs for an Achilles tendinopathy, both characteristics must be kept in mind.

Aetiology of the Achilles tendinopathy

Understanding the clinical features related to the load deformation curve is necessary when investigating the aetiological factors of a chronic Achilles tendon injury. If the tissue is elongated between 4 to 8 % change in length, microscopic failure occurs, when collagen fibers start to slide past one another and fail (44). Since frequent cumulative microtraumata obstruct adequate repair, an overuse injury of the Achilles tendon may occur even if the tendon is loaded within its physiologic limits (56). An unbalance between the load of the sport activities and the loading capacity of the tendon leads to the chronic character of the Achilles tendon injury. Many risk factors, as described below, are thought to accelerate this process (2,8,14,22,33,38,42,43,44,47,54,55,62,65,66,83).

Prevention and intervention studies have become focal points for researchers and clinicians. For these types of studies can be designed well, the risk factors for the injury must be clearly established. As stated before, the aetiology of an Achilles tendinopathy remains unclear, but is multifactorial, resulting from a combination of intrinsic and extrinsic risk factors (55). Many injury risk factors, both extrinsic (those outside of the body) and intrinsic (these from within the body) have already been suggested. Changes in training patterns, poor technique, previous injuries, footwear, and environmental factors such as training on hard, slippery, or slanting surfaces are considered extrinsic factors that predispose an athlete to a tendon overuse injury (8,14,38,55,83).
In addition to these extrinsic factors, possible intrinsic risk factors for an Achilles tendinopathy have been mentioned in literature. Almost all studies that investigate *age* as a possible risk factor agree that chronic tendon injuries in general are significantly more common in aging athletes. For example, Kannus et al. carried out a 3-year prospective, controlled study of sport injuries in elderly athletes in order to determine the number,

profile, and specific features of these injures compared with those of 'young' athletes (43). They concluded that tendon complaints in the elderly athletes were significantly more common than among young athletes. In a review of Kvist the authors stated that Achilles tendon overuse injuries occur at a higher rate in older athletes than most other typical overuse injuries (55). No data were listed in this review article(55). The review article of Alfredson and Lorentzon state that the peak incidence for an Achilles tendon injury is situated between age 35 and 45 (2). Probably this hypothesis is made on the basis of the practical experience of the researchers. In another study, Fahlström examined competitive badminton players retrospectively and found that there was a correlation between age and tendon pain in that examined middle – aged group (33). The prevalence and characteristics of painful conditions in the Achilles tendon region were examined in 32 middle – aged competitive badminton players by means of questionnaire and physiotherapist's examination. Pain in the Achilles region was reported by 44%, either presently or during the past 5 years, generally localized in the middle portion of the tendon. Age was found to be correlated to Achilles tendon pain in these middle – aged badminton players (33). The authors also concluded that there was no relationship between symptoms of pain and body mass index, gender, training quantity, or years of playing badminton (33). As a consequence of aging, a decreased blood supply to the tendon has been suggested as a causal factor (37). Kannus and Jozsa evaluated specimens obtained from the biopsy of spontaneously ruptured tendons in 891 patients who were treated between 1968 and 1989 (44). The specimens included 397 Achilles tendons. Ninety – seven percent of the pathological changes were degenerative, and most of them included hypoxic degenerative tendinopathy (44).

Several *biomechanical 'abnormalities'* are also mentioned as possible intrinsic risk factors. Increased foot pronation has been proposed to be associated with Achilles tendinopathy (66). The article of Nigg is based on a critical analysis of the literature on heel – toe running addressing kinematics, kinetics, resultant joint movements and forces, muscle activity, subject and material characteristics, epidemiology, and biological reactions (66). In this review article, excessive foot eversion and/ or tibial rotation movements have been proposed to increase the chance of overuse syndromes such as patellofemoral pain syndromes, shin splints, Achilles tendinitis, plantar fasciitis, and stress fractures (66). No exact data were presented in this article. In the study of Clement and co – authors, 109

runners were treated conservatively for overuse injury to the Achilles tendon (22). Retrospectively some etiologic factors were examined. The three most prevalent etiological factors were overtraining (82 cases), functional overpronation (61 cases), and gastrocnemius/soleus insufficiency (41 cases). Komi and co – workers have shown that increased pronation can result in increased EMG amplitude in the dorsiflexor muscles and decreased EMG amplitude in the plantarflexor muscles (54). Moreover, the overpronation results in a 'wringing' or twisting action of the Achilles tendon (54). McCrory et al. concluded on the basis of a retrospective study that a varus deformity of the forefoot correlates with Achilles tendinopathy (62). The purpose of this study was to determine whether relationships exist between selected training, anthropometric, isokinetic muscular strength, and endurance, ground reaction force, and rearfoot movement variables in runners afflicted with Achilles tendinitis. The authors examined differences in selected measures between a noninjured cohort of runners and a cohort of injured runners (62). Isokinetic, kinetic and kinematic measures were collected. The goal of their study was to identify the factors that discriminate between the injured and control groups. Years of running, training pace, stretching habits, overpronation, plantar flexion peak torque at 180°. s^{-1}, and arch index were found to be significant discriminators (62).
Also *leg – length discrepancy* is mentioned to be a potential contributing factor (42). However, in the referred article no exact data are proposed.
In contrast, Aström has shown, in a thesis including 362 consecutive patients with chronic Achilles tendinopathy and 147 control patients, that biomechanical defaults were not important in chronic Achilles tendinopathy (8). It should be noted, however, that up to now only statistically significant associations have been found from retrospective studies. No prospective study has identified a definite cause – effect relationship.
Consequently, studies mentioned an association between an *altered joint mobility* and the occurrence of an Achilles tendinopathy. Kvist compared the mobility of athletes with Achilles tendinopathy and healthy athletes (55). He demonstrated that decreased mobility of the subtalar joint and limited range of motion of the ankle joint were significantly more frequent in athletes with Achilles tendinopathy (55). During 1976 – 1986, 3336 athletes consulted the Turku Sports Medical Research Unit, 455 (14%) of these athletes for Achilles tendon injuries. Achilles tendon problems were more frequent among joggers (66%), tennis players (32%), and runners (24%). A marked limited total passive subtalar joint mobility and/or ankle joint dorsiflexion with knee extended was found in 70% of the athletes with

Achilles tendon pain. Kaufman et al. investigated the relation between the foot structure and range of motion and lower extremity musculoskeletal overuse injuries among military recruits (47). The purpose of this prospective study was to determine whether an association exists between foot structure and the development of musculoskeletal overuse injuries. The study group was a well – defined cohort of 449 trainees at the Naval Sapatial Warfare Training Centre. Before beginning of the training, measurements were made of ankle motion, subtalar motion, and the static and dynamic characteristics of the foot arch. The subjects were tracked prospectively for injuries throughout training. The risk factors include dynamic pes planus, pes cavus, retricted ankle dorsiflexion, and increased hindfoot inversion (47). They concluded that an increased tightness of the gastrocnemius was also a risk factor for an Achilles injury (47).

However, the relationship between range of motion and Achilles tendon injury remains controversial. In a review of Murphy et al (65), 3 studies (12,47,82) reported an association between increased range of motion and lower extremity injury, whereas 4 (9,63,84,86) reported no association. Soderman et al. found knee hyperextension greater than 10° to be a risk factor for lower extremity injury in female soccer players (82). However, ankle dorsiflexion range of motion and hamstrings flexibility were not risk factors. Beynnon et al. showed that increased calcaneal eversion motion was a risk factor for ankle injury in female collegiate athletes, but not for male athletes (12). Kaufman et al. found that increased hindfoot inversion was a risk factor for Achilles tendinitis, but ankle and hindfoot motion were not risk factors for lower extremity stress fractures in military recruits (47). As mentioned above, four studies in the review of Murphy et al. reported no association (65). Twellaar et al. found no significant differences in terms of range of motion about ankle, hip and knee between physical education students who sustained lower extremity injuries and those who did not (84). In a study of lower extremity injury among dancers, Wiesler et al. did not find a relation between ankle range of motion and injury (86). Barrett et al. reported no relation between plantar and dorsiflexion range of motion and ankle injury among basketball players (9). In addition, Milgrom et al found no relation between hip internal and external rotation in male infantry recruits who sustained ankle injuries compared with those who did not (63).

A possible reason for the disagreement in the literature is that these studies investigated lower extremity injuries as a group and did not focus on the Achilles tendon in specific.

Finally, the importance of *muscle weakness and imbalance* in the development of a chronic Achilles tendon injury is also a matter of debate. Kannus stated that if a muscle is weak or fatigued, the energy – absorbing capacity of the muscle-tendon unit is reduced (42). In that case, the muscle no longer protects the tendon from strain injury (42). Alfredson et al. retrospectively found that the calf muscle strength on the injured side was significantly lower, both concentrically and eccentrically, compared with the non – injured side of middle - aged patients (5). However, no prospective studies have been executed.

In the current literature none of the discussed risk factors were confirmed by means of prospective cohort studies and studied an Achilles tendon injury in specific. A substantial problem of the frequently used retrospective investigations is that they do not provide conclusive evidence on whether the examined factors are the causes or the consequences of injuries (36). The lack of high – quality prospective studies limits the strength of the conclusions that can be drawn regarding these potential risk factors.

In conclusion, many intrinsic risk factors, frequently mentioned in literature, have no or poor scientific evidence. Consequently, studies with a prospective character, focusing on the Achilles tendon in specific are recommended.

Rehabilitation and prevention programs

As a consequence of the recent histopathologic findings, the effectiveness of treatment regimens with an anti – inflammatory goal, are highly questioned in the current literature. Nowadays, most authors agree that an intervention program for Achilles tendinopathy should consist of a combination of strategies aimed at controlling overuse and correcting possible extrinsic and intrinsic risk factors such as limb alignement, muscle weakness and decreased flexibility (2). A muscle – tendon unit should be both strong and elastic. As mentioned above, Alfredson et al. found that the calf muscle strength on the injured side was significantly lower compared to the non–injured side of middle-aged patients with Achilles tendinopathy (5). Otherwise, the relationship between the range of motion and an Achilles tendinopathy remains controversial. Some articles state that an increased flexibility is a risk factor for Achilles tendinopathy (12,47,82). Other studies reveal no association between range of motion and an Achilles tendinopathy (9,63,84,86). Nevertheless, it is stated in several review articles that the ankle joint should be stretched on a regular basis during the rehabilitation of an Achilles tendon injury (2,37,41,48).

All these data resulted in the fact that strength training and stretching have become the two cornerstones of an intervention program for an Achilles tendinopathy in the current literature.

In order to strengthen the muscle – tendon unit, eccentric training regimens have become very popular. Eccentric loading exercises involve active lengthening of the muscle – tendon unit. The Achilles tendon is loaded by having the subject stand at the edge of a step and allow the heel drop over the edge (4). Progression can be made by increasing the speed of movement or by increasing the magnitude of the tensile force through changing the external resistance. The overall progression of loading is determined by the clinical symptoms so that a "maximum load" is always applied (4). This means that the patient should feel some pain or little discomfort during the exercises. The clinical use of eccentric exercises was pioneered in the literature by Curwin & Stanish in 1984 (23). More recently, Alfredson et al. prospectively studied the effect of heavy load eccentric calf muscle training in Achilles tendinopathy. This patient group was compared to a control group that proceeded to surgery (4). The study found that all the subjects in the eccentric training group were back to their pre – injury levels with running activity and the effect in terms of pain reduction and prevention in strength deficits were significantly better compared to the control group (4). In comparison to previous studies, this study used only eccentric exercises and the exercises were executed with pain. However, despite promising results, many questions remain unanswered. For example, why is the program successful? Theoretically, it could be the effect of this training leading to tendon hypertrophy and increased tensile strength. Possibly, the effect of the stretching component of the eccentric exercise has a significant influence on the elastic tendon characteristics (2). Recent studies have also hypothesized that eccentric training has a sclerosing effect on the neovascularisation (69,71).

Traditionally, it is generally accepted that stretching promotes better performances and decreases the number of injuries (15,26,27,35,88,89). However, today the scientific evidence concerning these effects of stretching seems unclear (80,90). Nevertheless, exercises in order to increase flexibility are common practice on the athletic field. Therefore, stretching exercises are regularly included in warm-up sessions and cooling-down exercises. The three most common stretching techniques include proprioceptive neuromuscular facilitation (PNF), static stretching and ballistic stretching (77). Stretching is often used in rehabilitation and prevention programs for Achilles tendinopathy. However, today the scientific evidence concerning the preventive and curative effect of stretching on injuries seems unclear. Also the question which stretching technique is preferable used remains unanswered.

In conclusion, strength training and stretching are frequently used in conservative treatment programs and seems to lead to moderate and good clinical outcome.

Background and aim of this dissertation

The *first aim* of this dissertation was to gain a better insight into the intrinsic risk factors for the development of an Achilles tendinopathy (chapter 2 and 3).

Since the aetiology remains obscure in the literature and most research has been executed retrospectively, there is need for prospective cohort studies. Consequently, in **chapter 3**, a prospective study of intrinsic risk factors was performed in male recruits. Male officer cadets followed the same basic military training. The factors examined included anthropometrical characteristics, isokinetic ankle muscle strength, ankle joint range of motion, Achilles tendon stiffness (reliability study **chapter 2**), explosive strength, and leisure and sports activity. These factors were chosen on the basis of 1) their reliability of the testing methods, 2) the availability of the appropiate testing material, 3) the time schedule of the recruits and 3) the results of previous studies (5,28,31,46,61,65).

The *second aim* of this dissertation was to investigate which regimes could be used in prevention and rehabilitation programs (chapter 4 and 5).

In earlier studies, several authors state that adequate intervention strategies are still lacking (74).

Since an important function of the Achilles tendon is to initiate ankle movements by transferring muscle force to the calcaneal bone, many authors stated that increasing the strength of the plantar flexors should be the focus of prevention and rehabilitation programs. Despite the fact that eccentric training has been accepted as an appropiate strengthening method, new commercial intervention methods are constantly suggested. Sport coaches and physiotherapists try new methods in order to offer their athletes or patients a large assortment of training options. However, some of these relatively new training alternatives are insufficiently based on scientific evidence. All kinds of positive effects are presented by advertising. It is the duty of research studies to inform athletes and patients which effects of these training technologies are evidence based. One of these training methods is whole - body vibration.

Whole-body vibration has become increasingly popular as a strength training tool. Whole-body vibration (WBV) training is a training method which exposes the entire body to mechanical vibrations as the individual stands on a vibrating platform. Mechanical stimulations, characterized by a direction, an amplitude, a velocity and a frequency are transmitted through the entire body. Recent observations have shown the possibility of utilizing these vibration platforms as a training tool in an athletic setting (24,59,75). The observed improvements have been attributed to reflex muscle contractions as a result of a "tonic vibration reflex". This reflex contraction is caused by an excitation of muscle spindles leading to an enhancement of the activity of the Ia loop (18,19,76).

In **chapter 4**, a study was set up to examine the supplemental value of a whole-body vibration program in comparison to an equivalent traditional training program. The main purpose of the study was to investigate if a WBV program results in a higher strength gain compared to an equivalent exercise program performed without vibration. Because a decreased plantar flexor strength was detected as a risk factor for the development of an Achilles tendinopathy (**chapter 3**), the results of the study described in chapter 4 show wether or not WBV can be an interesting method to prevent an Achilles tendinopathy. However, further prospective studies should be done to confirm this hypothesis. In **chapter 4**, we also investigated the effect of whole-body vibration on postural control. This hypothesis does not directly relate to the main subject of this thesis. However, this parameter was chosen because in the literature concerning whole-body vibration it is highly questioned if a vibration program could have an effect on the postural control of healthy subjects.

Besides the strength management, obtaining an appropiate flexibility is seen as an second goal in the approach of tendon injuries. Therefore, stretching is often suggested as a second cornerstone of a prevention or rehabilitation program for an Achilles tendinopathy. Despite the fact that the preventive character of stretching is still debated in the literature (90), the two most commonly used stretching techniques 'on the field' are static and ballistic stretching. However, it has been stated in the past that ballistic stretching is disadvantageous, even harmful because the muscle may reflexively contract if restretched quickly (81). Therefore, many studies have been executed in order to define the real value of static and ballistic stretching (58,78,85,91). However, no single study has clarified if static and ballistic stretching have a different effect on different tissues. In **chapter 5**, different methods were used in order to detect the underlying mechanism for the increase in range of motion. The passive resistive torque of the plantar flexors during isokinetic passive motion of the ankle joint and the tendon stiffness measured by ultrasound imaging were assessed in order to define the effect of static and ballistic strething on the muscle – tendon tissue properties.

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CHAPTER 2

TEST-RETEST RELIABILITY OF MEASURING THE PASSIVE STIFFNESS OF THE ACHILLES TENDON USING ULTRASONOGRAPHY

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ABSTRACT

The purpose of this study was to examine the test – retest reliability for the real time ultrasonic measurement method that is used to determine the stiffness of the Achilles tendon. Twenty-one healthy men and women aged 20-50 years took part in the study. The subjects underwent three identical test sessions held seven days apart. The lengthening of the tendon during maximal isometric plantar flexion was determined using ultrasonography. A dynamometer was used to measure torque output during isometric plantar flexion. The relationship between the muscle force and the elongation of the tendon was calculated to become a measure of the stiffness of the Achilles tendon. The ICC for the stiffness of the right and the left Achilles tendon was 0.80 and 0.82 respectively, indicating a good reliability. The results demonstrate that this technique is reliable for the evaluation of the elastic properties of the Achilles tendon. This may be clinically important in the assessment of tendon properties.

KEY WORDS

Stiffness, tendon, ultrasonography, reliability

INTRODUCTION

According to Hill's classical model, the skeletal muscle – tendon complex consists of contractile and elastic components, the latter of which can be further divided into elements arranged in series with or parallel to muscle fibers [12,15,32,36]. The series elastic component is passively stretched by external force and interacts with the contractile component [43]. The series elastic component also functions as elastic energy storage and mechanical buffer. Anatomically, the series elastic component is composed of tendinous tissues (tendon and aponeurosis); epi -, peri -, and endomysium, sarcolemna, and endosarcomeric structures [38]. The tendon tissues play a very important part in the transmission of tension from the muscle fibre to the bone [29]. However, in most cases muscle fibres do not directly attach to the tendon but to the tendon plate or aponeurosis. An aponeurosis is an enveloping fascia that serves to bind muscles together. Since the aponeuroses are directly connected to the muscle fascicles, it is obvious that the strain distribution along the aponeurosis substantially affects the amount of fascicle shortening during contractions.

The elastic properties of tendon structures have been so far determined on the basis of human cadaver and animal experiments [6,47]. Recently progress in technology has made it possible to study the dynamics of the tendon structures *in vivo* with the use of ultrasonography [11,17,19-29]. In 1995, Fukashiro et al [11] proposed an ultrasonographic method to determine elastic properties of tendon structures *in vivo* in humans from the observations of lengthening of the tendon and aponeurosis during isometric ramp contractions.

In the literature concerning the mechanical properties of tendons, the quotient of the load to the elongation of the tendon has been calculated as an estimate of tendon stiffness [44]. Fukashiro et al. 1995 [11] claimed that one could determine the elastic properties of the Achilles tendon structures *in vivo* through the observation of the lengthening of the tendon and aponeurosis during isometric contractions of the plantar flexors.

Isometric contraction literally means no change in muscle fibre length during contractions. However, because the tendon elastic properties, there could be some shortening of muscle fibres and lengthening of the tendon even during isometric contractions, i.e. when the total length of the muscle – tendon complex is kept constant. This implies that the muscle fibres produce mechanical work where there is no apparent work done by the whole muscle-tendon complex [17] . In case of the Achilles tendon, an increase in plantar flexion torque is accompanied by shortening of muscle fascicles and lengthening of tendon and aponeurosis. This is in agreement with the results of previous animal experiments which report that during a fixed-end contraction, internal shortening of muscle fibers occurred due to tendon and aponeurosis elongation [16,40].

Moreover, Muramatsu et al. [38] measured and compared the strain of the human tendon and aponeurosis for human medial gastrocnemius muscle. There was no significant difference in strain between the Achilles tendon and aponeurosis. In addition, no significant difference in strain was observed between the proximal and the distal regions of the aponeurosis. These results indicate that the tendinous tissues of the medial gastrocnemius muscle (tendon and aponeurosis) are homogenously stretched along their lengths by muscle contraction.

The most important benefit of this technique is the fact that the measurements take place *in vivo*, in contrast with earlier studies on cadavers and animals [6,13,47]. In addition, the technique is non invasive. The technique can be used for several human tendons; the most commonly used is the Achilles tendon. Surprisingly, the test-retest reliability of the test has never been examined. The purpose of this study was hence to examine the test-retest reliability for the real time ultrasonic measurement method that is used to determine the stiffness of the Achilles tendon.

MATERIALS AND METHODS

Subjects

Twenty-one healthy volunteers (9 males, 12 females) participated in this study. The mean age of the subjects was 30.5 years (range 20-50 years). The mean body weight was 64.4 kg (range 53 – 82 kg). Subjects with a history or complaints of Achilles tendinopathy or lower limb trauma were excluded from the study. None of the participants was training for an athletic even during this study. All subjects signed an informed consent. The Ethical Research Committee of Ghent University approved the study. Each subject underwent three identical test sessions, each session held seven days apart and taking place on the same day of the week and at the same time of the day in an attempt to ensure consistent activity levels. Both legs were tested. The same examiner familiar with the method did all the tests and verified that the subjects did the same physical activity prior to the test.

Measurement of the torque

An isokinetic dynamometer (Biodex System 3®) was used to determine torque output during isometric plantar flexion. The subject lay prone on a bench. First, the right ankle was placed in a 90° position (anatomical position) with the knee joint at full extension and the foot securely strapped to a footplate connected to the lever arm of the dynamometer (Fig.1). The standard Biodex ankle unit attachment with the Biodex provided Velcro® straps was used in this study. To maintain the ankle joint and dynamometer axes alignment during plantar flexion contraction, the foot was firmly attached to the footplate of the dynamometer with a strap. The position and the height of the Biodex chair were recorded for each subject individually and were used in the following evaluations. Before the test, the subjects performed 3-5 submaximal contractions to be accustomed to the test procedure. After warm-up, the subjects were instructed to develop an isometric maximal voluntary contraction (MVC) during five seconds. The task was repeated three times per subject with 30 s rest between the trials. Each subject was verbally encouraged to exert maximal voluntary effort by contracting as hard as possible. The same protocol was repeated similarly for the left leg. Isometric strength was expressed as peak torque. The force of the tendon was estimated from plantar flexion torque, the physiological cross-sectional area ratio of the medial gastrocnemius to all the plantarflexors, and the moment arm. Consequently, the value of the calculated force was used for the data analysis.

Measurement of elongation of the tendon

To obtain a measurement of the elongation of a tendon, the method of Fukashiro [11] was used. The contractile component activates and the muscle-tendon unit shortens during a concentric activation but only the muscle belly shortens during an isometric activation. Therefore, increase in plantar flexion is accompanied by shortening of fascicles and lengthening of the tendon and the aponeurosis, this indicates that the muscle fibers produced mechanical work, which was observed in the tendon even in the so-called isometric contraction. In the present study, a real-time ultrasonic apparatus (Siemens® Sonoline SL-1) was used to obtain a longitudinal ultrasonic image of the medial gastrocnemius (MG) muscle at 30 % of the lower leg (i.e. central). An electronic linear array probe of 7.5 MHz wave frequency was secured with Velcro® straps on the skin (Fig. 1). The ultrasonic images were recorded on videotape (Digital Camera Sony®). The tester visually confirmed the echoes from the aponeurosis and the MG fascicles. Parallel echoes running diagonally represent the collagen-rich connective tissue between the fascicles of the medial gastrocnemius. The darker areas between the bands of echoes represent the fascicles. The echo that runs longitudinally in the middle is from the aponeurosis. The point (x) at which one fascicle was attached to the aponeurosis was visualised on the ultrasonic image. This point (x) moved proximally during isometric torque output. The distance travelled by x ($\triangle x$) is considered to indicate the lengthening of the aponeurosis and therefore also from the tendon [17,28,35,38] (Fig. 2). Measuring the displacement was done with the multimedia player, Light Alloy 1.D. The average score of the three measurements was used as a representative score for the elongation of the tendon (ELONG). Throughout the study, the same examiner who was familiar with the method performed all tests.

Figure 1: Measurement set-up. The subject lay prone on a bench. The ankle is placed in the anatomical position with the knee joint at full extension. A dynamometer (Biodex System 3®) was used to determine torque output during isometric plantar flexion. A real-time ultrasonic apparatus (Siemens® Sonoline SL-1) was used to obtain a longitudinal ultrasonic image of the Achilles muscle-tendon unit.

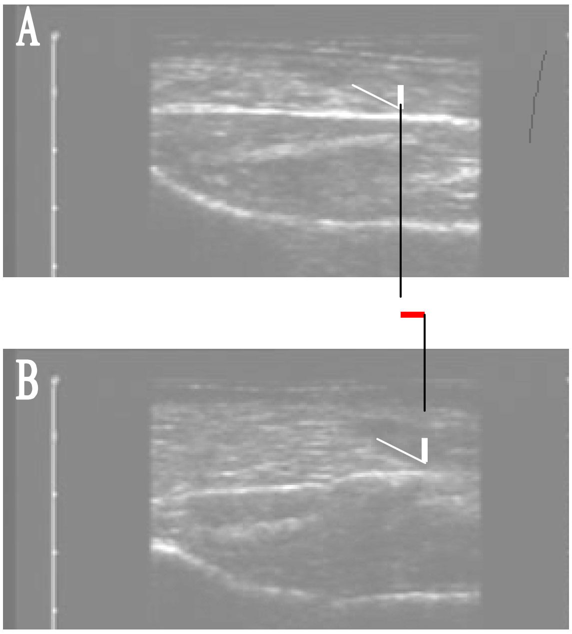

Figure 2: Measurement of elongation of muscle-tendon unit structures
Ultrasound images of longitudinal sections of the Achilles muscle-tendon unit at rest (A) and during isometric 100% maximal voluntary contraction (B). The distance travelled by the cross point (▬) was considered as the length change of the tendon structures during plantar flexion contraction.

Calculation of the stiffness of the Achilles tendon

The relationship between the supplied muscle force and the elongation of the Achilles tendon is calculated to become a measure of the stiffness of the Achilles tendon.

First, the measured torque TQ (N.m) during maximal isometric plantar flexion was converted to muscle force F_m (N) by following equation:

$$F_m = k.\ TQ.\ MA^{-1}$$

Where *k* is the relative contribution of the physiological cross-sectional area of the medial gastrocnemius within plantar flexor muscles (18%) [10] and MA is the moment arm length of triceps surae muscle at 90° of ankle joint (50mm) [33,39,46].

$$F_m = 18/100\ .\ TQ\ .\ (0.05)^{-1}$$

Secondly, the proportion between F_m and ELONG (N/mm) indicates the stiffness of the tendon (STIFFN). In this article, the calculations were used according to Kubo [28].

Statistics

Descriptive statistics were used to calculate the mean muscle force and the mean elongation values for the three testing sessions.

Test – retest data were analysed using the Intraclass Correlation Coefficient (two – way mixed effects model average measure reliability – 3,k; in the nomenclature of Shrout and Fleiss [41]). Another indicator of reliability is the 'Standard Error of Measurement' (SEM). This within – subject standard deviation is also known as the typical error in a measurement. It expressed the band of confidence around an individual 's raw score. It is an estimate of error to use in interpreting an individual's test score. The most common way of calculating this statistic that is cited in the sport science literature is by the means of the following equation: $SEM = SD \times (1- ICC)^{0.5}$ where SD is the sample standard deviation and ICC is the calculated Intraclass Correlation Coefficient [5]. In case of a perfect agreement the SEM is zero and any change is a true one. The use of SD in the equation, in effect, partially 'cancels out' the interindividual variation that was used to the calculation of the ICC [3]. The 95% confidence range of Standard Error of Measurement was calculated using the expression $95\%SEM = 1.96 \times 2^{0.5} \times SEM^{0.5}$ where SEM is the calculated 'Standard Error of Measurement'. The interpretation of the Standard Error of Measurement is analogous to the standard deviation; in the sense that the latter measures variability among individuals in the population, the former measures variability among samples [3,4,8,14]. For comparison across sample, measurement error was also expressed as the SEM% ($SEM\% = (SEM/mean) \times 100$) to produce a unitless indicator of error magnitude.

Stiffness as well as elongation and force were analysed in order to evaluate the different aspects of the method. In addition, differences in force, elongation and stiffness were analysed with a General Linear Model one-way ANOVA for repeated measures for each of our dependent variables with one within-subject factor (time - with three levels). The alpha level was set on 0.05. All statistical analysis was performed using SPSS® for Windows® (Version 10.0, SPSS, Inc., Chicago, IL) software.

RESULTS

The descriptive data for the muscle force (F_m), elongation (ELONG), and the stiffness values of the muscle – tendon unit ($STIFFN = F_m/ELONG$) for the three testing sessions are summarized in Table 1. The corresponding ICC–coefficients, p-values from the ICC-coefficients, SEM, 95%SEM and SEM% are summarized in Table 2. The test-retest Intraclass Correlation Coefficient values (ICC 3,k) were the highest for the muscle force values (0.95 and 0.96). The Intraclass Correlation Coefficient values for the elongation of the right and the left muscle-tendon unit of the subject were respectively 0.78 and 0.87. However, the clinically most important values were the Intraclass Correlation Coefficients for the stiffness of the muscle-tendon unit (0.80 and 0.82). SEM-values were 27.77 N and 29.58 N, 0.89 mm and 0.68 mm, 6.89 N/mm and 8.06 N/mm respectively for the right and the left leg. The values for 95%SEM amounted to 14.61 N and 15.07 N, 2.61 mm and 2.29 mm, 7.28 N/mm and 7.87 N/mm. SEM% - values were 8.51 % en 9.19 % for the muscle force, 13.90 % and 10.15 % for the elongation and 12.98 % and 15.83 % for the stiffness, respectively for the right and the left leg.

Table 1: Mean and Standard Deviations (SD) for the muscle force (F_m), elongation (ELONG) and stiffness (STIFFN) of the left (L) and the right (R) muscle-tendon unit.

	Week 1		Week 2		Week 3	
	Mean	SD	Mean	SD	Mean	SD
F_m L [N]	321.7	128.6	314.8	156.3	318.3	147.9
F_m R [N]	326.2	120.6	299.5	139.6	309.8	124.2
ELONG L [mm]	6.7	2.0	6.0	1.9	5.9	1.9
ELONG R [mm]	6.4	2.0	5.4	1.9	6.2	1.9
STIFFN L [N/mm]	50.9	24.4	55.8	25.2	54.7	19.0
STIFFN R [N/mm]	53.1	19.6	56.7	19.4	51.3	15.4

Table 2: Reliability indices for the muscle force (F_m), elongation (ELONG) and stiffness (STIFFN) of the left (L) and the right (R) muscle-tendon unit: Intraclass Correlation Coefficient (ICC), Standard Error of Measurement (SEM), 95% Confidence Range of Standard Error of Measurement (95%SEM) and SEM% (SEM/mean x 100). The p-values from the Intraclass Correlation Coefficients (ICC p-value) are also presented.

	ICC	ICC p-value	SEM	95%SEM	SEM%
Fm L [N]	0.96	P< 0.001	29.58	15.07	9.19 %
Fm R [N]	0.95	P< 0.001	27.77	14.61	8.51 %
ELONG L [mm]	0.87	P < 0.001	0.68	2.29	10.15 %
ELONG R [mm]	0.78	P < 0.001	0.89	2.61	13.90 %
STIFFN L [N/mm]	0.82	P < 0.001	8.06	7.87	15.83 %
STIFFN R [N/mm]	0.80	P < 0.001	6.89	7.28	12.98 %

DISCUSSION

Establishing the reliability of a technique is an essential, though insufficient, prerequisite for its implementation as a clinical tool. Reproducibility may be expressed using different techniques but probably the most relevant is the error of measurement which indicates the amount of fluctuation at the individual level. For this purpose, the SEM is an effective tool. Using the average values as a denominator and the SEM of each of the parameters as the numerator, an estimate of the size of the error relative to the base measurement is obtained. Thus for example the relative SEM (SEM%) for F_m is less than 10% (e.g. (29,58/321.7) x100), indicating acceptable reproducibility. To render decision applicable at group level, the ICC is a suitable option. According to Fleiss [9], good reliability is demonstrated by an ICC of > 0.75. Intraclass Correlation Coefficients of > 0.90 are considered to indicate excellent reliability for clinical use [5,9,45]. Thus, the results of the present study support the hypothesis that the present technique has acceptable reproducibility required for evaluating the stiffness of the Achilles tendon.

In this study, we calculated the stiffness of the Achilles tendon based on the elongation of the tendon and the muscle force. We found, in consistence with our expectations, that the reliability of the muscle force measurement was excellent, a finding indicated also in a previous study [7]. Our results show slightly lower values for the measurement of the elongation of the Achilles muscle-tendon unit. Magnusson [37] states that careful considerations need to be made about measuring the elongation. First, since the technique is based on the displacement of intramuscular fascicular structures that can be observed on the ultrasound image, the resulting deformation does not represent that of the muscle – tendon unit per se, but rather the total deformation of the combined tendon and aponeurosis (tendon structures) distal to the measurement site. Second, the method accounts only for two dimensions of structural deformation (i.e., in the sagittal plane), and cannot account for deformation in three dimensions. Third, although ultrasonography is applied during "isometric" conditions, it has been shown that the very slight joint rotation which was likely to take place could markedly affect the displacement measurements.

In the present study, the delivered force of the plantar flexors was estimated from the plantarflexion torque, physiological cross – sectional area of the medial gastrocnemius to all the plantar flexors and the previously reported moment arm. Maganaris et. al. [31] defined the moment arm as the distance between the joint center of rotation and the muscle line of action. We used one moment arm length for all subjects, despite variations in moment arms among subjects. However, we believe that the individual variations in a very homogenous population like our test population, play a secondary role. To determine the individual moment arm, sagittal plane MRIs could be obtained with the ankle in neutral position using the Reuleaux method as previously described [30,34]. It should be borne in mind that it is impossible to obtain an MRI on a regular basis. However, despite these limitations we suggest that the findings derived from present technique are clinically reproducible and should therefore be introduced appropriately while vindicating their validity.

CONCLUSION

It is well recognised that the muscle-tendon unit plays an important role in the mechanical energy storage and recovery during locomotion [1,2]. Increased stiffness of a tendon has been shown to be a predisposing factor for exercise-related injuries [42]. Consequently, examination of the elastic properties of the tendon may be indicated. For that to be a viable option the technique used must be shown to be reproducible and valid. This article indicates that real time ultrasonic measurement method yields reproducible measures of the Achilles tendon stiffness. The ability to measure the stiffness of a human tendon implies that several therapeutic interventions designed to alter the stiffness can be evaluated and compared. Moreover, understanding the exact role of the elastic properties could help in optimizing training and rehabilitation guidelines.

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CHAPTER 3

INTRINSIC RISK FACTORS FOR THE DEVELOPMENT OF ACHILLES TENDON OVERUSE INJURY

a prospective study

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ABSTRACT

Background: Although Achilles tendon overuse injuries occur commonly, our understanding of the pathologic changes and the factors that predispose athletes to them is limited.

Purpose: To indentify measurable intrinsic risk factors for Achilles tendon overuse injuries.

Study Design: Cohort study (prognosis); Level of evidence, 2.

Methods: Sixty - nine male officer cadets followed the same six week basic military training. Before this training, each subject was evaluated for anthropometrical characteristics, isokinetic ankle muscle strength, ankle joint range of motion, Achilles tendon stiffness, explosive strength, and leisure and sports physical activity. During military training, Achilles tendon overuse injuries were registered and diagnosed by the same medical doctor. To identify the intrinsic risk factors in this study, a multivariate analysis with the use of stepwise logistic regression was performed. The sensitivity, the specificity ,and cutoff values of the risk factors were evaluated by receiver operating characteristics curve analysis.

Results: Ten of the 69 male recruits (14.5 %) sustained an Achilles tendon overuse injury diagnosed on the basis of medical history and clinical examination. Analysis revealed that male recruits with lower plantar flexor strength and increased dorsiflexion excursion were at greater risk of Achilles tendon overuse injury. The cutoff value of the plantar flexor strength at 85% sensitivity was 50 N.m with a 4.5% specificity; the cutoff value of the dorsiflexion range of motion at 85% sensitivity was 9.0°, with 24.2% specificity.

Conclusion: The strength of the plantar flexors and amount of dorsiflexion excursion were identified as significant predictors of an Achilles tendon overuse injury. A plantar flexor strength lower than 50.0 N.m and dorsiflexion range of motion higher than 9.0° were possible thresholds for developing an Achilles tendon overuse injury.

KEY WORDS

muscle strength, ankle range of motion, prospective, Achilles tendon overuse injury, military recruits

INTRODUCTION

Overuse injuries of the muscle- tendon unit, resulting from leisure activities, sports, and military training, represent a major problem. They account for approximately 30 to 50 % of all sports injuries [23,25]. Of these overuse injuries, Achilles tendon problems are frequent, especially in people who run often[27]. In a cohort study with 11 years of follow – up, Kujala et al. reported that 79 (29%) of the 269 male orienteering runners and 7 (4%) of 188 controls reported an Achilles tendon overuse injury on a questionnaire; the age – adjusted odds ratio was 10.0 in runners compared with controls [33].

Although Achilles tendon overuse injuries occur commonly, the identification of the factors that predispose athletes to them is limited. The strength, imbalance, and flexibility of the muscles are frequently mentioned in the literature as possible intrinsic risk factors. However, these proposed risk factors have been based on the results of retrospective studies or the clinical experience of sports medicine experts [30,36]. Review articles agree that well-devised prospective studies of the possible risk factors for an Achilles tendon overuse injury are lacking. Because no high - quality prospective studies are yet available, the conclusions that can be drawn regarding possible intrinsic risk factors are limited [48].

The purpose of this study was therefore to investigate if some of these proposed intrinsic risk factors contribute to the development of Achilles tendon overuse injuries. To obtain this goal, we designed a comprehensive, prospective cohort study in military recruits.

MATERIALS AND METHODS

Study population

Sixty – nine male officer cadets volunteered for the study; these persons were recruited from the 191 male cadets entering the Belgian Royal Military Academy in August 2003. Ethical approval was obtained from the Ethics Committee of the Belgian Department of Defense. All participants were orally briefed about the methods and aims of the study and gave written informed consent. The age of the subjects was 18.41 ± 1.29 years (mean ± SD). Height and weight measurements were obtained before the training. Body Mass Index (BMI) was calculated as weight x height $^{-2}$.

Basic Military Training

All 69 male officer cadets in this study followed the same 6-week basic military training during the same period (August - September 2003). This training mainly consists of running, roadwork, military tactical exercises, drills, shooting, marching with backpacks, and some theoretical classes. Because all recruits followed the same training program with the same equipment, environmental conditions, food, and daily schedule, the extrinsic contributing factors that could affect the incidence of Achilles tendon overuse injuries were kept mainly under control.

Before starting the 6-week training period, each subject completed a questionnaire and underwent the same physical tests (muscle strength, range of motion measurement, stiffness of the Achilles tendon, and explosive strength).

Questionnaire

The questionnaire was intended to assess the subject's exercise, medical, and injury histories of the past 2 years. It was completed according to guidelines provided by an instructor, who was also present throughout the session. Subjects were briefed on each section of the questionnaire, were asked to answer each question honestly, and were informed that their responses would be kept strictly confidential and would be only seen by one of the study investigators (N.N.M.). This investigator was not related to the Belgian Department of Defense. The questionnaire also included a subjective assessment of the subject's current physical fitness level [2]. To estimate physical activity patterns, the Baecke questionnaire was used [2].This inventory quantifies work, sports and leisure activities using a 5-point scale with descriptors ranging from *never* (1 point) to *always* (5 points). For instance, a sports activity index was calculated as intensity × time engaged and was proportional according to yearly participation. By adding the scores on the 3 items of the Baecke questionnaire, the global activity of each subject was calculated. Research has shown that this questionnaire is a valid and reliable tool to measure physical activity [49,50].

Evaluation of muscular strength

Before the beginning of the training, each cadet's calf muscle strength was evaluated. The isokinetic performance of the calf muscles was measured with a Cybex Norm dynamometer (Lumex, Inc., Ronkonkoma, NY), which was calibrated as part of the regular schedule of equipment maintenance for the testing device [11]. The same investigator (V.S.), who was familiar with isokinetic testing, performed all tests. Plantar flexors and dorsiflexors were concentrically measured at 30 deg/s (3 repetitions) and 120 deg/s (5 repetitions). Before the tests, subjects received instructions about the procedures and were asked to perform a warm – up familiarization exercise of 10 submaximal repetitions at 90 deg/s. All subjects were tested in the standard position for testing ankle kinetic movement according to the guidelines of the Cybex system [11]. For assessment, the subject lay supine with the knee fully extended, and the foot was placed on a footplate and strapped twice for further stabilization. The ankle joint was aligned with the axis of the dynamometer. The reference angle corresponded to the ankle's neutral position (90°). The movement range covered the entire comfortable range of motion of subject's ankle joint. The other leg was strapped with Velcro® (VELCRO USA Inc, Manchester, NH) to avoid compensatory movements. All testing was conducted with the subject's hands placed on the hips.

Subjects were instructed to give 100% effort and received positive feedback during testing. Between each test, the cadets were allowed to rest for 1 minute. The same protocol was repeated similarly for the other leg. Alternatively, the right leg and the left leg were tested first. The peak torque values of the plantar flexors and the dorsiflexors were used for data analysis.

Range of motion measurement

Ankle joint range of motion was measured with a universal goniometer (NV Gymna, Bilzen, Belgium) and by the same investigator (N.N.M) to provide consistent intrarater reliability. Both ankles were evaluated. For this measurement, the subject was positioned supine with both limbs supported and the foot projected off the end of the table so that the ankle movement was unimpeded. Maximal range of motion was evaluated with the knee in two positions, 45° flexed and extended. Measurements taken with the knee flexed were considered to represent primarily soleus extensibility, whereas the measurements with the knee in extension were considered to be influenced primarly by gastrocnemius extensibility [55]. Care was taken to maintain a neutral calcaneal position during all evaluations. The bony landmarks used for these assessments were defined with the method used by Elveru et al [15]. The proximal arm of the universal goniometer was aligned with the head of the fibula, and the axis of the goniometer was positioned 0.5 cm below the lateral malleolus. The distal arm was aligned parallel to an imaginary line joining the projected point of the heel and the base of the fifth metatarsal. The subject was asked to perform maximal active plantar flexion and dorsiflexion. Consequently, the same measurements were taken passively. These measurement were found to be valid and reliable [3,6,14,15,34,42,45,46,51-53]; in a study of Elveru et al, the intraclass correlation coefficient (ICC) values were 0.85 for plantar flexion and 0.90 for dorsiflexion [15].

Stiffness of the Achilles tendon

To identify Achilles tendon stiffness, the ultrasonic measurement technique described by Fukashiro was used [18]. These researchers determined the elastic properties of the Achilles tendon structures in vivo by observing the lengthening of the tendon and aponeurosis during isometric contractions of the plantar flexors [18]. The test - retest reliability of measuring Achilles tendon stiffness using ultrasonography has been shown to be good (ICC, 0.80-0.82) [40].

Measurement of torque

A dynamometer (Biodex System 3, Biodex Medical Systems Inc, Shirley, NY) was used to determine torque output during isometric plantar flexion. The subject lay prone on a bench. First, the right ankle was placed in a 90° position (anatomical position) with the knee joint at full extension and the foot securely strapped to a footplate connected to the lever arm of the dynamometer. The standard Biodex ankle unit attachment with Biodex-provided Velcro® straps was used in this study. To maintain ankle joint and dynamometer axis alignment during plantar flexion contraction, the foot was firmly attached to the footplate of the dynamometer with a strap. Before the test, the subjects performed 3 to 5 submaximal contractions to become familiar with the procedure. After warm - up, subjects were instructed to develop an isometric maximal voluntary contraction during 5 seconds. The task was repeated 3 times per subject with a 30-second rest between the trials. Each subject was orally encouraged to exert maximal voluntary effort by contracting as hard as possible. The same protocol was repeated similarly for the left leg. Isometric strength was expressed as peak torque. The force of the tendon was estimated from plantar flexion torque, the physiological cross - sectional area ratio of the medial gastrocnemius to all the plantarflexors, and the moment arm [32]. Consequently, the value of the calculated force was used to determine the stiffness of the Achilles tendon.

Measurement of elongation of the tendon

As described earlier, the method of Fukashiro was used to obtain the measurement of tendon elongation[18]. The contractile component activates and the muscle - tendon unit shortens during a concentric activation, but only the muscle belly shortens during an isometric activation. Therefore, an increase in plantar flexion is accompanied by a shortening of the fascicles and lengthening of the tendon and aponeurosis. This process indicates that the muscle fibers produce mechanical work, which was observed in the tendon even in the so - called isometric contraction. During isometric plantar flexion on the Biodex dynamometer in the present study, a real - time ultrasonic apparatus (Sonoline SL-1, Siemens AG, Erlangen, Germany) was used to obtain a longitudinal ultrasonic image of the medial gastrocnemius muscle at 30 % of the lower leg (ie, central). An electronic linear array probe with a wave frequency of 7.5 MHz was secured with Velcro® straps to the skin. The ultrasonic images were recorded by a digital camera (Sony Corp, Tokyo, Japan). The tester visually confirmed the echoes from the aponeurosis and the medial gastronemius fascicles (Figure 1). The point at which 1 fascicle was attached to the aponeurosis was visualised on the ultrasonic image. This point (x) moved proximally during isometric torque output. The distance travelled by x ($\triangle$x) indicated the lengthening of the aponeurosis and therefore also the tendon [21, 32, 39,43]. The displacement was measured with a multimedia player, Light Alloy 1.D (Softdepia, Nicosia, Cyprus), and the average score of the 3 measurements was used as a representative score for tendon elongation (ELONG). The same examiner (N.N.M.) who was familiar with the method, performed all tests throughout the study. The obtained value, together with the calculated force was used to compute the stiffness of the Achilles tendon.

Calculation of Achilles tendon stiffness

The relationship between the supplied muscle force and the elongation of the Achilles tendon was calculated to obtain a measurement of Achilles tendon stiffness. First, the measured torque during maximal isometric plantar flexion, TQ, was converted to muscle force, F_m, by the following equation:

$F_m = k. TQ. MA^{-1}$,

where k is the relative contribution of the physiological cross - sectional area of the medial gastrocnemius within plantar flexor muscle (18%) and MA is the moment-arm length of triceps surae muscle at 90° of ankle joint (0.05m) [19,38,54,65].

$F_m = 18/100 \cdot TQ \cdot (0.05)^{-1}$

The proportion between F_m and ELONG (N/mm) indicates the stiffness of the tendon. In this article, the calculations used were according to Kubo [32].

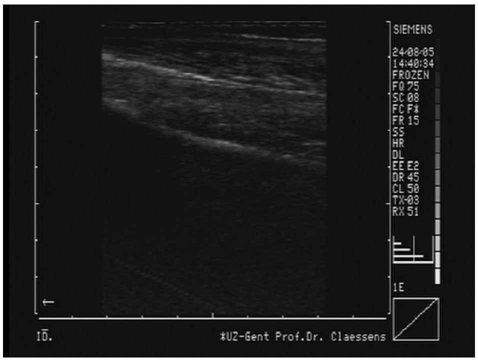

Figure 1: Parallel echoes running diagonally represent the collagen-rich connective tissue between the fascicles of the medial gastrocnemius. The darker areas between the bands of echoes represent the fascicles. The echo that runs longitudinally in the middle is from the aponeurosis.

Explosive strength

The standing broad jump was used to measure explosive strength. This test was chosen because it represents an explosive type of movement. In addition, it is commonly used in the training and testing of athletes in various sports, and was found to be highly reliable (ICC = 0.984) [16,28]. The standing broad jump correlates well with the other types of explosive movement such as the vertical jump and sprinting [1,12,61].

The jump required takeoff and landing from a single foot. Takeoff was from behind a line on the floor, and subjects were instructed to land on the same foot they used for takeoff. The distance from the takeoff to the point where the heel touched the mat was measured. The broad jump was executed 3 times for each leg, and the best of the 3 recorded trials was used as the performance score.

Registration of injuries

During the training, overuse injuries of the Achilles tendon were registered and diagnosed by the same doctor (P.R.) and were listed on separate sheets containing information about the injury. To be considered a patient with an Achilles tendon overuse injuy, the following criteria needed to be present: 1) characteristic history and symptoms of an Achilles tendon overuse injury (stage I, II, III and IV of the injury criteria by Blazina et al [8]); 2) impaired performance, and 3) pain. The combination of Achilles tendon pain and impaired performance indicated the clinical diagnosis of an Achilles tendon overuse injury. Patient history and the moment of onset indicated the overuse nature of the injury. Subjects with an insertional Achilles tendinopathy were excluded from the study. Local tenderness had to be present and was evaluated by palpating the tendon with the ankle in neutral position or slightly plantar flexed. The tendon had to be thickened over a length of 2 to 5 centimeters. This area may or may not have demonstrated increased warmth, depending on the extent and duration of the overuse injury. Resisted plantar flexion and passive dorsiflexion at the ankle had to worsen the pain, making it difficult for a patient to stand on the toes or to climb stairs. Morning stiffness needed to be present. An injury was only considered if it was serious enough for the subject to seek and obtain medical consultation and if it resulted in 1 or more days of limited duty. To be included in the study, a recruit had to have all of the listed characteristics. Persons with injuries to the skin and subcutaneous tissue, such as abrasions and blisters, were not included. In this study, we were primarily interested in studying first-incidence Achilles tendon overuse injuries. Because previous tendon injury is an important and well-established intrinsic risk factor for musculotendinous injuries, we excluded all recruits who had sustained a muscle injury to the lower extremities in the previous two years [10,17,23,24,36,37,48,59,60].

Statistical procedures

Statistical analysis was performed with SPSS version 11.0 (SPSS Inc, Chicago, Ill). To examine possible differences between the injured and uninjured group for each test parameter (interval or ratio data), we used either the Student t test (if the distribution of the data was normal) or the Mann-Whitney U test (if no normal distribution of the data was obtained). A *P* value less than 0.05 was considered significant.

Logistic regression analysis was then performed to establish the presence of the major risk factors for Achilles tendon overuse injuries. Bivariate Ors of the variables with 95 % confidence intervals (CIs) were calculated for injured and noninjured subjects. The CIs were calculated using $\alpha = 0.05$, meaning that we had a 95 % chance that the true OR was between those 2 boundary marks. Consequently, all variables were entered into a forward stepwise logistic regression analysis. A logistic model for the prediction of an Achilles tendon overuse injury was obtained, with adjusted ORs of the variables with their 95% CIs. The Hosmer and Lemeshow test was used to test the fit of the models [20].

The sensitivity, specificity and cutoff values of the obtained risk factors were evaluated by receiver operating characteristic (ROC) curve analysis. These ROC analyses allows an investigator to determine possible cutoff values. A list of specificities and sensitivities for subsequent cutoff values was calculated [29,41,67]. To decide how likely these statistics would be able to detect significant effects in this given sample size, a power analysis was executed for the different variables.

RESULTS

Ten of the 69 male recruits (14.5 %) sustained a clinically diagnosed Achilles tendon overuse injury. According to the injury criteria of Blazina et al.[8], 1 subject sustained a stage I, 4 subjects sustained a stage II, 5 subjects developed a stage III, and no one sustained a stage IV (complete rupture of the Achilles tendon) (Table 1).

The characteristics of the 10 cadets who sustained an Achilles tendon overuse injury, measured before the start of the military training, were statistically compared with those of the cadets without an Achilles tendon overuse injury.

Table 1: Classification of the Achilles tendon overuse injures [a].

Injury Stage	Criteria	No. of Injured subjects (n = 10)
I	Pain only after sports activity	1
II	Pain at the beginning of sports activity, disappearing after warm-up, and reappearing with fatigue	4
III	Constant pain at rest and during activity; subject unable to participate in sports at previous level	5
IV	Complete rupture of the Achilles tendon	0

[a] According to injury criteria used by Blazina et al. [8]

Anthropometric evaluation and physical activity

Anthropometric data on the subjects are listed in Table 2. No significant differences were found between the injured and the uninjured recruits in height, weight or BMI (P = .107, .619, and .083, respectively). In addition, statistical analysis did not reveal any significant difference in physical activity between the injured and the uninjured recruits (P = .639) (Table 2).

Table 2: Anthropometric data and physical activity levels for injured and uninjured subjects.

	Injured		Uninjured			
Variable	Mean	SD	Mean	SD	t^a	P
Age, y	18.00	1.49	18.47	1.26	1.070	0.288
Height, cm	177.50	7.85	183.6	6.74	1.635	0.107
Weight, kg	72.00	13.60	70.46	8.08	-0.499	0.619
Body mass index	22.73	3.00	21.41	2.04	-1.759	0.083
Baecke Questionnaire score	8.69	0.64	8.87	1.21	0.472	0.639

[a] *t*, the test statistic for the Student *t* test.

Muscular strength

Significant differences were found for all plantar force measurements except for one (plantar flexors of the left leg at 120 deg/s; P = .128). For all other plantar flexor measurements, the injured group produced significantly less plantar flexor force than the noninjured group before the military training. No statistical significant differences were observed between both groups for the dorsiflexion force measurements ($P > .05$) (Table 3). The statistical power for the plantar flexor strength measurement was .819.

Range of motion

Table 4 represents the evaluated range of motion data. Statistical analyses of the goniometric measurements revealed no significant differences between the groups. However, a tendency towards significance (P = .076) was observed for the right passive dorsiflexion measurement with the knee extended. For this measurement, the injured recruits seem to have a higher dorsiflexion range of motion in comparison to the uninjured recruits at the start of the military training. The statistical power for the range of motion measurements was .314.

Table 3: Isokinetic muscle strength and jump performances for injured and uninjured subjects.

	Injured		Uninjured			
	Mean	SD	Mean	SD	t [a]	P
Dorsiflexion strength, N.m						
30 deg/s						
Right leg	22.20	4.18	21.24	4.72	-0.605	.547
Left leg	21.80	6.53	21.44	5.29	-0.192	.848
120 deg/s						
Right leg	11.70	1.57	11.14	3.19	-5.46	.587
Left leg	11.30	2.98	11.66	3.38	0.317	.752
Plantar flexion strength, N.m						
30 deg/s						
Right leg	66.60	12.04	83.42	25.05	2.074	.042[b]
Left leg	69.00	19.10	87.56	26.19	2.141	.036[b]
120 deg/s						
Right leg	33.90	9.46	43.76	13.37	2.232	.029[b]
Left leg	37.80	12.04	45.19	14.30	1.541	.128
SBJ[c] performance, cm						
Right leg	162.00	17.35	163.05	17.79	0.173	.863
Left leg	163.50	17.17	164.15	17.55	0.109	.913

[a] t, the test statistic for the Student t test.
[b] Significant difference between the 2 groups ($P < .05$).
[c] SBJ, standing broad jump.

Stiffness of the Achilles tendon

Results of the analysis performed for Achilles tendon stiffness are presented in Table 5. No significant statistical differences were observed between groups in stiffness for the right and the left Achilles tendons (P = .117 and .166, respectively). The statistical power for the stiffness measurement was .781.

Explosive strength

No statistical differences were found between the injured and uninjured recruits in standing broad jump performance (P = .863 and .913, for the right and left leg, respectively) (Table 3). The statistical power for the explosive strength measurement was .069.

Table 4: Range of motion data (in degrees) for injured and uninjured subjects.

	Injured		Uninjured			
	Mean	SD	Mean	SD	*t* or U[a]	*P*
Plantar flexion						
45° flexed						
Right active	38.20	5.69	40.81	6.25	*t* = 1.237	.220
Right passive	42.00	6.04	44.47	6.35	*t* = 1.147	.255
Left active	41.20	9.81	40.83	8.13	*t* = -0.129	.898
Left passive	46.20	9.82	45.05	8.09	*t* = -0.403	.688
Extended						
Right active	43.20	6.05	45.05	8.92	*U* = 261.00	.556
Right passive	46.80	5.35	47.83	10.73	*U* = 273.50	.712
Left active	38.20	10.81	41.80	11.48	*U* = 207.00	.131
Left passive	42.00	10.11	45.36	12.16	*U* = 215.00	.171
Dorsiflexion						
45° flexed						
Right active	16.10	4.38	14.68	6.41	*t* = -0.674	.503
Right passive	20.60	5.17	18.03	5.68	*t* = -1.338	.186
Left active	18.40	4.79	15.19	6.02	*t* = -1.584	.118
Left passive	23.40	4.43	20.00	6.59	*t* = -1.567	.122
Extended						
Right active	11.20	4.92	9.69	5.16	*U* = 220.50	.199
Right passive	15.20	5.35	12.95	5.39	*U* = 192.00	.076
Left active	13.00	10.25	12.81	9.67	*U* = 291.50	.953
Left passive	17.60	10.74	16.51	9.91	*U* = 276.00	.744

[a] t, the test statistic for the Student *t* test; *U*, the test statistic for the Mann-Whitney *U* Test.

Intrinsic risk factors

In many fields, the logistic regression model has become the standard method for analysis for studying the relationship between a binary response variable (in our case, presence of an Achilles tendon injury) and one or more explanatory variables (evaluated parameters) [19]. To identify the intrinsic risk factors in this study, a multivariate analysis was performed with the use of stepwise logistic regression. Table 6 represents the risk model for the prediction of an injury of the Achilles tendon as a result of a stepwise logistic regression analysis.

The strength of the plantar flexors and amount of dorsiflexion excursion were identified as significant predictors of an Achilles tendon overuse injury. The function of the best fitting model is as follows:

$$g(x)= (-0.009) + ((-0.062) \times (\text{PlanLe30})) + 0.207 \times (\text{PassDor right-straight})),$$

where PlanLe30 is the isokinetic plantar flexor strength of the left leg at 30deg/s, and PassDor right-straight is passive dorsiflexion range of motion of the right ankle with the knee extended.

After logit transformation, this following model predicts the risk of an Achilles tendon overuse injury.

$$\Pi(x) = \frac{e^{g(x)}}{1 + e^{g(x)}}$$

The outcome ranges between 0 and 1 and can therefore be interpreted as a percentage, where 0 represents no risk for an injury and 1 the highest possible risk. For example, if a recruit has a plantar flexor strength of 39 N.m and a dorsiflexion range of motion of 9° :

$$g(x)= (-0.009) + ((-0.062) \times (39)) + 0.207 \times (9)$$

$$g(x)= (-0.009)-0.555$$

$$g(x)= -0.564$$

After logit transformation,

$$\Pi(x) = \frac{e^{-0.564}}{1 + e^{-0.564}} = 0.36$$

The model predicts that this specific person has a 36% chance of developing an Achilles tendon overuse injury.

With the help of the ROC analysis, possible cutoff values of the 2 intrinsic risk factors were determined at 85%, 90% and 95% sensitivities for detecting an Achilles tendon overuse injury. The results of the ROC analysis are presented in Table 7.

The cutoff value of the plantar flexor strength at 85% sensitivity was 50 N.m with a 4.5% specificity. The cut – off value of the dorsiflexion range of motion at 85% sensitivity was 9.0°, with 24.2% specificity.

Table 5: Stiffness data (in N/mm) for injured and uninjured limbs.

	Injured (n=20)		Uninjured (n=66)		t [a]	P
	Mean	SD	Mean	SD		
Right leg	35.69	13.86	47.59	22.85	1.590	.117
Left leg	31.57	8.12	40.20	17.98	1.404	.166

[a] t, the test statistic for the Student t test.

Table 6: Risk model for the prediction of an Achilles tendon injury versus no injury[a].

Predictive variable	B	SE	OR	95% CI	*P*
PlanLe30, N.m	-0.062	0.025	0.940	0.895-0.987	.014
PassDor right-straight, deg	0.207	0.089	1.230	1.033-1.465	.020
Constant	-0.009				

[a] Model obtained by binary logistic regression. B, regression coefficient; SE, standard error ; OR, bivariate odds ratio ; 95%CI, 95% confidence interval ; PlanLe30, isokinetic plantar flexor strength of the left leg at 30deg/s; PassDor right-straight, passive dorsiflexion range of motion of the right ankle with the knee extended.

Table 7: Cutoff values of the risk factors with respect to the sensitivity and specificity [a].

	85% sensitivity		90% sensitivity		95% sensitivity	
Parameter	Cutoff	Specificity, %	Cutoff	Specificity, %	Cutoff	Specificity, %
PlanLe30, N.m	50.0	4.5	42	3.0	39	1.5
PassDor right- straight, deg	9.0	24.2	7.0	6.1	5.0	3.0

[a] Sensitivity is defined as the proportion of all injured cases that were correctly identified as such; specificity is defined as the proportion of all uninjured cases that were correctly identified as such. PlanLe30, isokinetic plantar flexor strength of the left leg at 30 deg/s; PassDor right-straight, passive dorsiflexion range of motion of the right ankle with the knee extended.

DISCUSSION

Although Achilles tendon overuse injury is frequently encountered in the sports injury clinic, its risk factors remain obscure. Several authors cite both extrinsic and intrinsic parameters as causing Achilles tendon overuse injury [24,36,37,48,60]. Various extrinsic risk factors have already been clearly recognized; changes in training patterns, poor technique, previous injuries, footwear, and environmental factors such as training on hard, slippery, or slanting surfaces are extrinsic factors which may predispose the athlete to tendon overuse injury [24,36,37,48,60]. However, the relationship between intrinsic parameters and the occurrence of an Achilles tendon overuse injury is still obscure. Therefore, the purpose of this study was to investigate which intrinsic risk factors play a part in the development of an Achilles tendon overuse injury. In order to obtain this goal, a prospective study with male military recruits was designed. Because all subjects followed the same training program with the same equipment, environmental conditions, food, and daily schedule, the impact of extrinsic risk factors was kept to a minimum in the design of the present study. This was the reason we investigated a military population.

One of the most striking findings in our study was that the strength of the plantar flexors was identified as a predictor for an Achilles tendon overuse injury, with subjects having a lower plantar flexor strength at greater risk. The cutoff value with the highest specificity, can be seen as a possible threshold value. Consequently, persons with a plantar flexor strength lower than 50.0 N.m were predisposed to an Achilles tendon overuse injury. Several previous prospective studies have shown muscle strength or muscle imbalance to be risk factors for an ankle injury [4,13,57]. However, this is the first study that investigates the relationship between the strength of the plantar flexors and an Achilles tendon overuse injury in a prospective manner. The results reflect that persons with a lower plantar flexor strength have a significantly higher risk of developing an Achilles tendon overuse injury. Presumably, greater muscle strength produces stronger tendons that could deal better with high loads.

During the basic military training, the muscle - tendon unit is exposed to many stretch - shortening cycles. During these cycles, the muscle - tendon unit must be able to absorb high forces. A recruit with less plantar flexor strength is less able to absorb these forces and consequently has a higher risk for an overuse injury of the Achilles tendon simply because he has weaker tendons. In that way, it would be interesting to investigate which injury prevention programs would be able to incorporate the structure and mechanical properties of the Achilles tendon. In the literature, the experimental knowledge of the effect of strength training on tendon tissue is scarce and clinical human studies are lacking. With regard to human tendon structures, available information on the subject is limited to the cross – sectional observations [26, 31]. Because the power of this parameter reached an accepted level (.819), we can conclude that the given sample size was large enough to detect a significant effect for plantar flexor strength.

In the present study, greater dorsiflexion excursion has also been identified by the logistic regression analysis as a risk factor for an Achilles tendon overuse injury. Recruits with significant higher dorsiflexion range of motion have a greater risk of developing an Achilles tendon overuse injury. A possible threshold, defined from the ROC curve analysis, is a dorsiflexion range of motion of 9.0° (with a sensitivity of 85% and a specificity of 24.2%). Surprisingly, the Mann-Whitney *U* test revealed no significant difference between the injured and the uninjured group. However, there was a tendency to significance and this may explain this statistical oddity. Another reason for the parameter being recognised as a risk factor despite the lack of a difference between the groups is the rather low power of the test (.314). This result implies that presumably a larger sample is needed to find significant differences between the injured and uninjured group for the flexibility measurements.

Recently, Song et al. have shown that the severity of a strain injury in the gastrocnemius of rats depends on the excursion of the ankle [58]. These authors observed that the larger the range of motion of the ankle joint, the more damage was seen after an eccentrically induced strain injury. This finding may explain the clinical findings in our military population, which suggest that the more an ankle can dorsiflex during stretch – shortening cycles, the more an Achilles tendon is susceptible to an overuse injury.

Looking at the literature, the relation between range of motion and lower extremity injury remains controversial. In a review by Murphy et al, 3 studies reported an association between increased range of motion and lower extremity injury, whereas 4 reported no association [44]. A possible reason for the disagreement in the literature, is that these studies investigated lower extremity injuries as a group and did not focus on specific pathologic factors.

The results of this study revealed no significant relationship between any of the anthropometrical characteristics and the occurrence of Achilles tendon overuse injury. Our results are in agreement with a number of studies that have reported no association between body size and injury [4,5,7,35,47,62,66]. For example, Knapik et al did not find height, weight, or BMI to be risk factors for musculoskeletal injuries among male and female military recruits [30].

In our study, we did not find any relationship between the physical activity and the risk for an Achilles tendon injury. In contrast, other prospective studies on lower extremity injuries have shown a relationship between physical fitness and injury incidence [9,22,27,30,63]. Chomiak et al found that poor physical condition was a predictor of overall injury in football players [9]. The different results between these previous studies and this one might be explained by the difference in the method that was used to obtain measurements of physical activity. The level of physical activity in our study was determined on the basis of a questionnaire; other studies used physical fitness tests suwh as run time measurements or VO_2 (oxygen consumption) determinations. In addition, potential candidates for a military career are aware that good physical condition is a prerequisite for a successful military study career. As a consequence, the physical condition of our study population was possibly higher and more homogeneous compared with the population used in other, nonmilitary prospective studies. However, determining the level of physical activity on the basis of a questionnaire can be considered as a weakness of the present study.

In the present study, the stiffness of the Achilles tendon was not seen as an intrinsic risk factor for an Achilles tendon overuse injury. However, the power of this parameter was of an acceptable level (.781). The fact that no significant differences could be found between the injured and the uninjured group, was therefore not because of a low power. This finding might be in contrast with the conclusions of previous studies. In a review of Smith, increased stiffness of a tendon has been shown to be a predisposing factor for exercise–-related injuries [56]. Because most of the discussed studies were executed retrospectively however, one can not say with certainty if the altered stiffness of the tendon was a cause or a consequence of the overuse injury.

Knowing that the contribution of the calf muscles and Achilles tendons is rather limited in the performance of the standing broad jump might be a possible explanation to why there a significant difference was not found between the injured and the uninjured recruits for explosive strength. Previous studies have demonstrated that the glutei, the hamstrings and the quadriceps muscle determine for the greater part of jump performance, more than the calf muscles [64].

CONCLUSION

Our study identified increased dorsiflexion range of motion and decreased plantar flexion strength as intrinsic risk factors for the development of an Achilles tendon overuse injury. The statistical analyses revealed that recruits with a plantar flexor strength lower than 50 N.m and a dorsiflexion range of motion more than 9.0°, were predisposed to an Achilles tendon overuse injury during basic military training. When interpreting these results, however, not only the strengths but also the limitations of the study have to be considered. Therefore, we advise investigators to maintain the prospective character of the present study and to include a larger sample and to screen their population as best as they can.

Nevertheless, the results of the present study have important clinical implications, and adequate prevention strategies need to take the present results into account.

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CHAPTER 4

IMPROVING STRENGTH AND POSTURAL CONTROL IN YOUNG SKIERS: WHOLE-BODY VIBRATION VERSUS EQUIVALENT RESISTANCE TRAINING

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ABSTRACT

Context: Several groups have undertaken studies to evaluate the physiologic effects of whole-body vibration (WBV). However, the value of WBV in a training program remains unknown.

Objective: To investigate whether a WBV program results in a better strength and postural control performance than an equivalent exercise program performed without vibration.

Design: Randomized, controlled trial.

Setting: Laboratory.

Patients or other participants: Thirty - three Belgian competitive skiers (ages 9 –15 years).

Intervention(s): Subjects were assigned to either the WBV group or the equivalent resistance (ER) group for 6 weeks of training at 3 times per week.

Main Outcome Measure(s): Isokinetic plantar and dorsiflexion peak torque, isokinetic knee flexion and extension peak torque, explosive strength (high box test), and postural control were assessed before and after the training period.

Results: Both training programs significantly improved isokinetic ankle and knee muscle strength and explosive strength. Moreover, the increases in explosive strength and in plantar - flexor strength at low speed were significantly higher in the WBV group than in the ER group after 6 weeks. However, neither WBV training nor ER training seemed to have an effect on postural control.

Conclusions: A strength training program that includes WBV appears to have additive effects in young skiers compared with an equivalent program that does not include WBV. Therefore, our findings support the hypothesis that WBV training may be a beneficial supplementary training technique in strength programs for young athletes.

KEY WORDS

Balance, explosive strength, performance enhancement, skiing

INTRODUCTION

Whole-body vibration (WBV) training is a training method that exposes the entire body to mechanical vibrations as the individual stands on a vibrating platform. Mechanical stimulations, characterized by direction, amplitude, velocity and frequency are transmitted through the entire body. Recent observations have shown the possibility of using these vibration platforms as a training tool in athletic settings [1-3]. These improvements have been attributed to reflex muscle contractions as a result of a tonic vibration reflex. This reflex contraction is caused by an excitation of muscle spindles, leading to an enhancement of the activity of the Ia loop [4,5,6].

Most of the authors who have evaluated the effects of WBV have shown that muscular properties can be improved with its use [3]. For example, Bosco et al. showed that a single vibration bout of 5 repetitions lasting 1 minute each resulted in a significant temporary increase in muscle strength of the lower extremities and arm flexors [7]. In another study, Bosco et al. trained volleyball players with 10 repetitions at 60 seconds each [8]. Bosco et al. also studied the effects of a 10-day vibration program on the muscular performance of physically active persons and noted enhanced explosive power [9]. Other authors investigated the effects of WBV programs using randomized, controlled study designs [10-13]. For example, Torvinen et al. randomized 56 young adults to either a vibration group or a control (no training) group [11]. Jumping power was enhanced 8.5 % after a 4-month WBV intervention. More recently, investigators demonstrated that WBV training has the potential to induce strength gains to the same extent as a traditional resistance training program [1,2,12,13]. Consequently, on the basis of these studies, we can conclude that WBV is a training method equivalent to conventional resistance training.

However, despite the growing popularity of WBV, authors of a recent review claimed that it still lacks randomized scientific research, especially concerning its adaptation to dynamic exercises [3]. To date, only 1 author has undertaken a study to determine the supplemental value of WBV with an equivalent training program [14]. Ronnestad compared the performance-enhancing effects of squats on a vibration platform with conventional squats executed on the ground [14]. Thus, identical exercises were executed in both groups. The intervention period lasted 5 weeks. Although the results did not reach the level of statistical significance, the trend was toward better results in maximal strength and explosive power for the squats performed on a vibration platform. In order to further investigate this possibility, our purpose was to evaluate the training effects of a WBV program compared with an equivalent exercise program performed without vibration.

METHODS

Experimental design

We randomly divided 33 competitive skiers into a WBV group (n = 17) and an equivalent resistance (ER) training group (n = 16). Both groups trained for 6 weeks with a frequency of 3 times a week, with at least 1 day of rest between sessions. Each training session lasted 30 minutes, including warm-up exercises, rest periods and cool-down. After each session, the subjects were asked to report possible side effects or adverse reactions in their personal training diaries. After every training week, they also completed a Borg scale, a simple method of rating perceived exertion [15]. Before starting the study, as well as after the 6 weeks of training, we evaluated all subjects for postural control and isokinetic and explosive strength.

Subjects

The subjects were 33 competitive skiers (age = 12.36 ± 1.71 years; range = 9-15 years) of the Flemish Ski Federation: 12 girls and 21 boys (WBV = 11 boys and 6 girls; ER = 8 boys and 8 girls). We excluded skiers with a history of any type of injury in the last 2 years or a possible contraindication for WBV (diabetes, epilepsy, metabolic or neuromuscular diseases, osteoporosis, osteoarthrosis, prosthesis, menstrual irregularities and orthopaedic injuries, according to Roelants et al [2]). Persons who were already participating in another strength program were excluded from the study as well. All children and their parents gave written informed consent to participate. The study was approved by the Ethical Committee of Ghent University. The anthropometric and training characteristics of the subjects are presented in Table 1.

Table 1. Subjects' Anthropometric and Training Characteristics

	Whole-Body Vibration Training group (n = 17: 11 boys, 6 girls)		Equivalent Resistance Training Group (n = 16: 8 boys, 8 girls)		
	Mean	SD	Mean	SD	*p*
Age, y	12.94	1.47	11.75	1.77	.044
Height, m	1.6	0.12	1.49	0.14	.031
Mass, kg	50.14	13.06	38.79	12.11	.015
History of competitive skiing, y	4.03	1.55	3.75	2.58	.706
Participation in other sports, h/wk	1.91	2.07	1.94	1.77	.970
Training in summer, h/wk	2.32	2	2.46	1.9	.833
Training in winter, h/wk	4.76	1.48	4.75	1.03	.974

Whole-Body Vibration Training

Vibration loading was carried out on a WBV platform (Fitvibe; N.V. Gymna, Bilzen, Belgium) in a standing position. The program consisted of squatting, deep squatting, wide-stance squatting, 1-legged squatting, calf raises, skiing movements, jumps onto the plate, and light jumping (Table 2). After each exercise, the skiers were allowed to rest 2 minutes before starting the following exercise. Training intensity was increased over the 6 weeks by increasing the amplitude (from 2 to 4 mm) and frequency (from 24 to 28 Hz) of the vibration, the duration of the exercise, and the number of repetitions. Also the number of repetitions of 1 exercise and the number of different exercises increased systematically over the 6-week training period. During all training sessions, the subjects completed a personal exercise diary and were under the strict supervision of a physiotherapist.

Equivalent resistance training

In order to achieve the goal of our study, the ER training was composed of exactly the same exercises as the WBV training. The only difference was that the ER training group did not perform the exercises on a vibration platform but on the floor. Subjects in both groups wore sport shoes during the training sessions. They completed a personal exercise diary and were contacted every week for supervision of their training program. Every week, a physiotherapist conducted a joint training session with both groups to teach the new exercises being added to the programs.

Table 2. Whole-Body Vibration Training Program

		Exercise	Frequency, Hz	Amplitude, mm	Duration, s	Rest time, s	Repetitions, No.	Vibration Duration, min
Week 1	Day 1	Squat	24	2	30	60	3	4.5
		Calf raises	24	2	30	60	3	
		Wide-stance squat	24	2	30	60	3	
	Day 2	Squat	24	2	30	60	3	6.5
		Deep squat	24	2	30	60	3	
		Wide- stance squat	24	2	30	60	3	
		1-legged squat	24	2	30	60	2 x each leg	
	Day 3	Squat	24	2	30	60	4	8
		1-legged squat	24	2	30	60	2 x each leg	
		Dynamic squats	24	2	40	60	3 x 20	
		Dynamic calf raises	24	2	40	60	3 x 20	
Week 2	Day 1	Calf raises	24	2	30	60	4	8.7
		Deep squat	24	2	30	60	4	
		Dynanmic wide-stance squat	24	2	40	60	3 x 20	
		Dynamic squat	24	2	40	60	4 x 20	
	Day 2	Squat	24	2	40	60	4	11
		1-legged squat	24	2	40	60	2 x each leg	
		Dynamic calf raises	24	2	40	60	4 x 20	
		Jumps on plate	24	2	90	60	2 x 10	
	Day 3	Squat	26	2	30	60	4	8.7
		Calf raises	26	2	30	60	4	
		Dynamic wide-stance squat	26	2	40	60	4 x 20	
		Dynamic 1-legged squat	26	2	60	60	2 x 20 each leg	
Week 3	Day 1	1- legged squat	26	2	30	60	2 x each leg	10.3
		Jumps on plate	26	2	90	60	2 x 10	
		Dynamic calf raises	26	2	40	60	4 x 20	
		Dynamic squat	26	2	40	60	4 x 20	
	Day 2	Wide-stance squat	26	2	40	60	4	8.2
		Dynamic 1-legged squat	26	2	60	60	2 x 20 each leg	
		Dynamic inversion-eversion	26	2	40	60	3 x 15	
		Jumps	26	2	30	60	3 x 10	
	Day 3	Calf raises	26	2	40	60	4	14
		Dynamic wide-stance squat	26	2	60	60	4 x 30	
		Jumps on plate	26	2	100	60	2 x 10	
		Dynamic inversion-eversion	26	2	50	60	3 x 20	
		Squat	26	4	30	60	3	
Week 4	Day 1	Deep squat	26	4	30	60	3	8
		Dynamic squat	26	4	60	60	3 x 30	
		Wide-stance squat	26	4	30	60	3	
		1-legged squat	26	4	30	60	2 x each leg	
	Day 2	Calf raises	26	4	40	60	4	9.3
		Dynamic inversion-eversion	26	4	40	60	3 x 15	
		Dynamic 1-legged squat	26	4	60	60	2 x 20 each leg	
		Dynamic wide-stande squat	26	4	40	60	4 x 20	
	Day 3	Squat	28	2	30	60	3	10.2
		Dynamic calf raises	28	2	40	60	4 x 20	
		Dynamic wide-stande squat	28	2	60	60	4 x 30	
		Dynamic inversion-eversion	28	2	40	60	3 x 15	
Week 5	Day 1	Deep squat	28	2	40	60	3	13
		1-legged squat	28	2	40	60	2 x each leg	
		Jumps on plate	28	2	90	60	2 x 10	

		Dynamic squat	28	2	50	60	4 x 25	
		Dynamic skiing	28	2	40	60	3 x 15	
	Day 2	Wide-stance squat	28	4	30	60	3	8.2
		Jumps	28	4	40	60	3 x 20	
		Dynamic inversion-eversion	28	4	40	60	3 x 15	
		Calf raises	28	4	40	60	4	
	Day 3	Jumps on plate and hold	28	4	90	60	1 x 5 each leg	11
		Jumps	28	4	40	60	3 x 20	
		Dynamic skiing	28	4	60	60	4 x 25	
		Wide-stance squat	28	4	60	60	2	
Week 6	Day 1	Squat	28	4	60	60	2	11
		Jumps on plate and hold	28	4	90	60	1 x 10 each leg	
		Dynamic squat	28	4	60	60	2 x 40	
		Dynamic skiing	28	4	60	60	4 x 25	
	Day 2	Dynamic calf raises	28	4	40	60	4 x 20	13.3
		Dynamic wide-stance squat	28	4	50	60	4 x 25	
		Jumps on plate	28	4	100	60	2 x 15	
		Dynamic skiing	28	4	60	60	4 x 25	
	Day 3	Dynamic skiing	28	4	60	60	4 x 25	12.7
		Dynamic 1-legged squat	28	4	60	60	2 x 25 each leg	
		Dynamic squat	28	4	60	60	2 x 40	
		Jumps	28	4	40	60	4 x 20	

Evaluation

Isokinetic muscle strength

Isokinetic performance of the right calf muscles was measured with a Biodex System 3 isokinetic dynamometer (Biodex Medical Systems Inc, Shirley, NY). The dynamometer was calibrated as part of the regular schedule for maintenance of equipment used for the testing device.

Plantar flexors and dorsiflexors of the right ankle were concentrically measured at 30°. s^{-1} (3 repetitions) and 120°. s^{-1} (5 repetitions). All subjects assumed the standard position for testing isokinetic ankle movement, according to the guidelines of Dvir [16]. This protocol is reliable [17]. The subject was positioned in the chair with the knee fully extended. The right foot was placed on a footplate and held in place with 2 tight straps for further stabilization. The ankle joint of the subject was aligned with the axis of the dynamometer. The reference angle corresponded to the ankle's neutral position (90°). The movement range covered the entire comfortable active range of motion of the subject's ankle joint. Above the knee, the leg was restricted with hook-and-loop straps to avoid compensatory flexion movements. Before the tests, the subject received instructions about the procedures and was requested to perform a warm-up of 10 submaximal repetitions. This warm-up procedure allowed subjects to become familiar with performing isokinetic exercises on the Biodex dynamometer. The same investigator (N.N.M.), who was familiar with isokinetic testing, performed all tests. During the test, subjects were instructed to

give 100% effort and received positive feedback. The values of the peak torque (N.m) of the right plantar flexors and dorsiflexors were used for the data analysis. The peak torque was determined as the single repetition with the highest muscular force output (Nm) of the multiple test trials.
The right knee flexor and extensor muscles were tested concentrically at 60°. s^{-1} and 180°. s^{-1}, according to the guidelines of Dvir [16]. The person was strapped into the chair, using the right lateral femoral condyle as an anatomical reference for the axis of rotation on the Biodex [16]. This protocol is reliable [18]. The subject completed 5 repetitions of knee flexion and extension at a speed of 60 °. s^{-1} and ten repetitions at 180 °. s^{-1}. The upper leg, hips and shoulders were stabilized with safety belts. The subject was instructed to submaximally flex and extend the knee 10 times at each speed to become familiar with the procedure. The principal investigator (N.N.M.) instructed the subject to extend and flex the knee at full force throughout the test. The values of the peak torque (Nm) of the right knee flexors and extensors were used for the data analysis.

Explosive strength
We chose the high box test to assess some more ski-specific explosive strength, agility and coordination [19,20]. Significant correlations have been noted between the skiing performance time and the high box test [19,21]. In our study, a box with a height of 30 cm was used. The subject started by standing beside the box. On command, the subject jumped laterally up onto the box and then down off the other side. This was done continuously for 90 seconds. Performance was the number of jumps completed in 90 seconds [19].

Postural control
We tested postural control with the Balance Master (NeuroCom International, Inc., Clackamas, OR). The vertical ground reaction forces were used to calculate the position of the center of pressure and the equivalent centre-of-gravity (COG) sway angles. The reproducibility of the postural control tests on the Balance Master has been reported to be good to excellent [22]. Each subject was allowed to become familiar with the system and performed 1 test trial before proceeding to the tests. The tests for postural control in our study were the limits of stability test and the rhythmic weight shift test.

The limits of stability test is a dynamic standing balance test that measures the stable support in a controlled manner [23]. The test was performed in bipedal stance. We asked the subject to shift

COG from the centre to each of the 8 peripheral targets. These targets were positioned forward, forward right, right, backward right, backward, backward left, left, and forward left. During the assessment, the location of the subjects' COG and the peripheral targets were displayed on a screen. The subject could control the COG by shifting weight. We instructed the subject to move the COG cursor on command as quickly and accurately as possible toward 1 of the targets located on the limits of stability perimeter and then hold a position as close to the target as possible. The subject was allowed up to 8 seconds to complete each trial. The subject was instructed to lean forward to the target as much as possible without bending the hips or lifting the heels or toes off the ground. Three values were used in the data analysis. The endpoint excursion is the distance travelled by the COG on the primary attempt to reach the target, expressed as a percentage of the limits of stability. The maximum excursion is the furthest distance travelled by the COG during the trial, and the directional control is a comparison of the amount of movement in the intended direction to the amount of extraneous movement; both values are also expressed as percentages.

The rhythmic weight shift test quantifies the subjects' ability to rhythmically move the COG from left to right and from forward to backward between 2 targets [23]. As in the limits of stability test, the subjects' COG is displayed on a screen as a cursor providing visual feedback. We instructed the subject to rhythmically move the COG cursor from side to side or front to back between the 2 targets. With the COG cursor, the subject was asked to follow an on-screen cue at the same speed as it moved between the endpoints. The 2 values measured were the directional control in the left-right excursion and in the front-back excursion. Both values are expressed as percentages, ie, a perfect directional control score equaled 100%.

Statistical procedures

We peformed the statistical analysis with the Statistical Package for the Social Sciences (version 11.0; SPSS Inc., Chicago, IL). The data were analyzed using the Kolmogorov-Smirnov test. Independent *t* tests were used to compare the baseline characteristics of the groups. Paired-sample *t* tests were calculated for within-group comparisons. Between-group differences were analyzed by means of independent *t* tests on the change scores of both groups. The change score of a group was defined as the increase or decrease from pretraining to posttraining by that group. We similarly evaluated the results of the Borg scales for perceived exertion on the basis of paired and independent *t* tests. The effect size associated with the changes for each measure in both groups was calculated by the following formula: (posttraining mean – pretraining mean) / pooled

SD of pretraining and posttraining. The effect size of the difference in change scores between the groups was calculated by the following formula: (WBV change score mean – ER change score mean) / pooled SD of WBV and ER change scores. According to Rhea [24], a value of less than 0.25 represents a trivial effect size; 0.25 to 0.50, a small effect size; 0.50 to 1.00, a moderate effect size; and more than 1.0, a large effect size. For all analyses, the level of statistical significance was set at $P \leq 0.05$.

RESULTS

Pretraining results

Independent *t* tests revealed no significant differences between the two groups at the beginning of the study (Table 3).

Table 3. Baseline Characteristics

	Whole-Body Vibration Training Group (n = 17)		Equivalent Resistance Training Group (n = 16)		
Test	Mean	SD	Mean	SD	*P* value
High box test, No. of repetitions	53.53	16.91	49.75	12.88	.478
Limits of stability test, %					
End point Excursions	76.94	7.10	78.37	9.42	.624
Maximum excursions	97.06	4.32	99.75	6.44	.167
Directional control	71.06	9.28	71.75	5.78	.801
Rhythmic weight shift test, %					
Right-left	75.24	7.65	72.94	21.41	.681
Forward-backward	65.53	15.24	61.50	26.92	.598
Knee strength, Nm					
Extension (60° . s^{-1})	92.35	30.68	78.50	48.27	.335
Flexion (60°. s^{-1})	66.36	20.61	53.33	27.22	.135
Extension (180°. s^{-1})	66.66	19.72	55.87	28.32	.216
Flexion (180°. s^{-1})	56.46	16.33	43.81	22.48	.076
Ankle strength, Nm					
Plantar flexion (30°. s^{-1})	70.82	22.81	60.62	25.66	.236
Dorsiflexion (30°. s^{-1})	11.20	5.37	7.76	5.04	.067
Plantar flexion (120°. s^{-1})	44.20	14.50	36.04	14.30	.114
Dorsiflexion (120°. s^{-1})	10.55	4.45	8.11	4.54	.286

Posttraining results

Equivalent resistance training group

Performance on the high box test increased significantly in the ER group after the training period (Table 4). Moreover, all isokinetic muscle strength values improved significantly except for dorsiflexion strength at low speed. None of the postural control measurements increased significantly except for the directional control during the limits of stability test. Most significant values showed a small effect size.

Table 4. Training Effects Within the Equivalent Resistance Training group

Test	Pretraining Value		Posttraining Value		*P* value
	Mean	SD	Mean	SD	(Effect size)
High box test, No. of repetitions	49.75	12.88	55.19	17.37	.012* (0.37)
Limits of stability test, %					
End point Excursions	78.37	9.42	82.88	5.82	.086 (0.59)
Maximum excursions	99.75	6.44	99.69	4.24	.973 (-0.01)
Directional control	71.75	5.78	77.88	7.42	.002* (0.94)
Rhythmic weight shift test, %					
Right-left	72.94	21.41	67.25	14.04	.212 (-0.32)
Forward-backward	61.50	26.92	72.56	9.48	.105 (0.56)
Knee strength, Nm					
Extension (60° . s^{-1})	78.50	48.27	94.08	44.74	.006* (0.35)
Flexion (60°. s^{-1})	53.33	27.22	60.21	25.02	.012* (0.27)
Extension (180°. s^{-1})	55.87	28.32	63.81	23.71	.003* (0.32)
Flexion (180°. s^{-1})	43.81	22.48	49.53	20.90	.006* (0.27)
Ankle strength, Nm					
Plantar flexion (30°. s^{-1})	60.62	25.66	68.18	25.82	.008* (0.30)
Dorsiflexion (30°. s^{-1})	7.76	5.04	12.92	13.77	.138 (0.51)
Plantar flexion (120°. s^{-1})	36.04	14.30	41.62	13.40	.006* (0.41)
Dorsiflexion (120°. s^{-1})	8.11	4.54	11.45	4.43	<0.001* (0.68)

* Significant difference between pretraining and posttraining, $P \leq .05$

Whole-Body Vibration Group

Performance on the high box test increased significantly after 6 weeks of vibration training (Table 5). Also, all ankle and knee isokinetic muscle strength measurements showed significant increases after the training period. Most postural control values did not increase significantly except for directional control during the limits of stability test and the left-right excursion of the rhythmic weight shift test. Most significant values showed a moderate effect size.

Table 5. Training Effects Within the Whole-Body Vibration Group

Test	Pretraining		Posttraining		*P* value
	Mean	SD	Mean	SD	(Effect size)
High box test, No. of repetitions	53.53	16.91	67.06	20.06	<0.001* (0.72)
Limits of stability test, %					
End point Excursions	76.94	7.10	80.47	8.90	.246 (0.43)
Maximum excursions	97.06	4.32	97.06	5.52	1.000 (0)
Directional control	71.06	9.28	75.84	6.74	.006* (0.58)
Rhythmic weight shift test, %					
Right-left	75.24	7.65	69.76	10.35	.007* (-0.60)
Forward-backward	65.53	15.24	71.29	10.40	.079 (0.44)
Knee strength, Nm					
Extension ($60° . s^{-1}$)	92.35	30.68	114.98	40.00	.004* (0.63)
Flexion ($60°. s^{-1}$)	66.36	20.61	74.25	22.38	.001* (0.36)
Extension ($180°. s^{-1}$)	66.66	19.72	82.38	28.41	<0.001* (0.63)
Flexion ($180°. s^{-1}$)	56.46	16.33	64.17	19.11	.011* (0.43)
Ankle strength, Nm					
Plantar flexion ($30°. s^{-1}$)	70.82	22.81	90.09	28.29	<0.001* (0.74)
Dorsiflexion ($30°. s^{-1}$)	11.20	5.37	16.99	9.99	.030* (0.71)
Plantar flexion ($120°. s^{-1}$)	44.20	14.50	52.06	16.62	.014* (0.50)
Dorsiflexion ($120°. s^{-1}$)	10.55	4.45	13.21	3.24	<0.001* (0.67)

* Significant difference between pretraining and posttraining, $P \leq .05$

Comparison between both training programs

The increased performance on the high box test in the WBV group was significantly greater than the increase in the ER group (Table 6). Moreover, the increase in plantar-flexor strength at low speed was also significantly higher in the WBV group. For all other values, we found no significant differences between the change scores of the groups. All significant values show a moderate effect size.

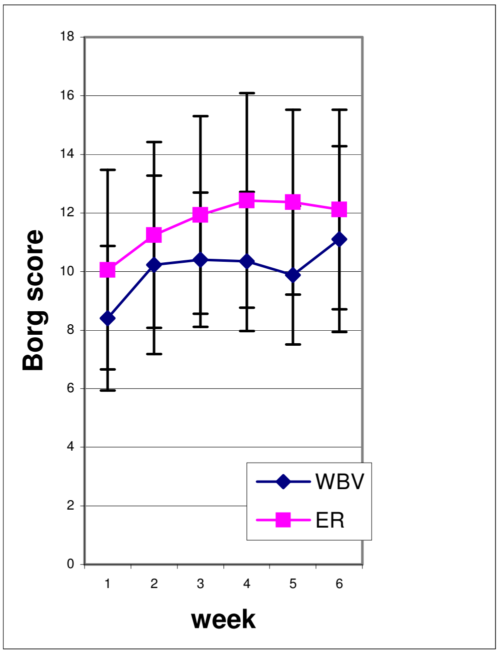
Perception of Exertion of the Exercise Programs

No significant differences wer noted between the WBV group and ER group, except for the Borg score of the fifth week, when the ER group rated the exercise program as more intense than the WBV group (Figure). Within each group, the Borg score in week 6 was significantly higher than the score in week 1.

Table 6. Comparison Between Training Programs

Test	Whole-Body Vibration Training Group		Equivalent Resistance Training Group		*P* value (Effect size)
	Change score	SD	Change score	SD	
High box testn No. of repetitions	13.53	9.79	5.44	7.66	.013* (0.92)
Limits of stability test, %					
End point Excursions	3.53	12.07	4.50	9.78	.802 (-0.09)
Maximum excursions	0.00	5.86	-0.06	7.38	.979 (0.01)
Directional control	4.88	6.38	6.13	6.52	.584 (-0.19)
Rhythmic weight shift test, %					
Right-left	-5.47	7.22	-5.69	17.46	.963 (0.02)
Forward-backward	5.76	12.68	11.03	25.62	.453 (-0.26)
Knee strength, Nm					
Extension (60° . s^{-1})	22.62	27.72	16.29	19.34	.466 (0.27)
Flexion (60°. s^{-1})	7.89	7.94	6.98	9.31	.766 (0.11)
Extension (180°. s^{-1})	15.71	14.74	8.61	9.34	.119 (0.58)
Flexion (180°. s^{-1})	7.71	10.98	5.61	6.68	.526 (0.23)
Ankle strength, Nm					
Plantar flexion (30°. s^{-1})	19.27	14.91	7.56	9.96	.013* (0.92)
Dorsiflexion (30°. s^{-1})	5.79	10.02	5.16	13.18	.879 (0.05)
Plantar flexion (120°. s^{-1})	7.87	11.74	5.59	6.94	.501 (0.23)
Dorsiflexion (120°. s^{-1})	3.01	4.17	3.12	4.46	.938 (-0.03)

* Significant difference between the change scores of the groups, $P \leq .05$



Perceived exertion of the training programs. Each value represents the mean Borg score of each training week. No significant differences were noted between the groups except during week 5 (P = .015). WBV indicates whole-body vibration training group; ER, equivalent resistance training group.

DISCUSSION

Both a WBV program and an ER training program improved isokinetic ankle and knee muscle strength and the explosive strength of the subjects after a 6-week training period. These findings are in accordance with those of several authors, affirming that WBV increases the dynamic strength of the lower extremity muscles [1,2,8,11]. Roelants et al. investigated the effects of 24 weeks of WBV on the knee extension strength in 89 postmenopausal women in a randomized controlled study [2]. Isokinetic and dynamic strength of the knee extensors increased both WBV and traditional resistance training groups, with the training effects not significantly different between the groups. Similarly, Delecluse et al. concluded that a WBV program can induce a strength gain in the knee extensors of previously untrained females to the same extent as a traditional resistance training program [1]. In these studies, the traditional resistance training programs and vibration programs consisted of different exercises. Therefore, whether WBV training had an additional training in value remains uncertain.

In our study, the ER training program consisted of exactly the same exercises as in the WBV group in order to evaluate the supplemental value of vibration training. Interestingly, our results reveal that the gains in explosive strength and in plantar-flexor strength at low speed were significantly higher in the WBV group than in the ER group after 6 weeks of training.
Using the same study design, Ronnestad concluded that the maximal strength of recreationally resistance-trained men increased significantly more after 5 weeks of a vibration program than after an equivalent training program [14].
Previous authors have tried to find a plausible explanation for these positive effects of vibration training. Some investigators have suggested that the large strength gain is the result of the result of the tonic vibration reflex [1,2,14,25]. They stated that standing on a vibration plate provokes length changes in the muscle that stimulate the muscle spindles. (In these studies, knee flexion and extension muscles were tested.) These receptors would elicit the tonic vibration reflex. In addition, it has been proposed that the recruitment thresholds of the motor units during WBV are expected to be lower than during voluntary contractions, probably resulting in a more rapid activation and training of high-threshold motor units [1]. Therefore, it has been suggested that WBV training specially trains fast – twitch fibers [1,26], which are responsible for explosive power.

In our results, the WBV group showed a significantly greater gain on the high box test than the ER group after 6 weeks of training. This finding is in agreement with the results of previous studies, that showed that WBV training has a positive effect on explosive strength. Delecluse et al. reported that jumping height increased significantly over 12 weeks in the WBV group and remained unchanged in the 3 other groups (control, placebo, and traditional resistance training) [1]. Also Ronnestad found a significant improvement of the vertical jumping height after subjects performed squats on a vibration platform for 5 weeks [14].

In our study, neither WBV nor ER training for 6 weeks resulted in a convincing effect on postural control. This finding is in agreement with that of Torvinen et al.[11], who showed that 4 months of vibration training produced no effect on the dynamic or static balance of young, healthy subjects. However, stroke patients with unilateral impairment showed an increase in their weight – shifting speed at the balance assessment after 1 session of WBV training [27]. In geriatric patients, WBV improved postural control [10]. After 4 months of training, chair-rising time improved 18 % in fit elderly participants, whereas the control group showed no significant differences. Consequently, we can speculate that WBV training only has a positive significant effect when the postural control of the subjects is disturbed.

In order to rate the perceived exertion of both training programs, each subject completed a Borg scale after each training week. No significant differences were noted between the groups, except during week 5, when the WBV group rated the exercises lower (easier). We know that the amplitude of the vibrations was reduced from 4 mm to 2 mm just before week 5, whereas the frequency was increased from 26 Hz to 28 Hz. It is possible that the amplitude of the vibrations had an important influence on the perceived exertion of the subjects. In previous studies, attention was only paid to the frequency of the vibrations.

The limitations of our study should be noted. Although the WBV training showed a significantly greater gain in explosive strength and in plantar flexor strength at low speed, we should take into account the fact that the WBV group was bigger and older than the ER group at baseline. Therefore, we have analyzed the change scores of both groups and not the absolute end values. In our study, no true control group was included. One could suggest that the young subjects might have had strength improvements regardless of training. Another limitation of our study was that we have not studied the length of the training effects. Therefore, future researchers should include a follow-up of the length of the training effects. Finally, not performing a Bonferroni correction in order to take type I errors into account when analyzing several dependent variables is also an important limitation of our study.

In conclusion, neither WBV training nor ER training seemed to have an effect on the postural control of young healthy skiers. However, both training programs improved isokinetic ankle and knee muscle strength and explosive strength after 6 weeks of training. Moreover, WBV training resulted in a significantly greater gain in explosive strength and plantar flexor strength at low speed compared with ER training after 6 weeks. Therefore, our findings support the hypothesis that WBV training can be a beneficial addition to traditional strength programs.

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CHAPTER 5

EFFECT OF STATIC AND BALLISTIC STRETCHING ON THE MUSCLE – TENDON TISSUE PROPERTIES

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ABSTRACT

Purpose: Many studies have been undertaken to define the effects of static and ballistic stretching. However, most researchers have focused their attention on joint range of motion measures. The objective of the present study was to investigate if static and ballistic stretching programs had different effects on passive resistive torque measured during isokinetic passive motion of the ankle joint and tendon stiffness measured by ultrasound imaging.

Methods: Eighty – one healthy subjects were randomised into three groups: a static stretch group, a ballistic stretch group and a control group. Both stretching groups performed a six week stretching program for the calf muscles. Before and after this period, all subjects were evaluated for ankle range of motion, passive resistive torque of the plantar flexors and the stiffness of the Achilles tendon.

Results: The results of the study revealed that the dorsiflexion range of motion was increased significantly in all groups. Static stretching resulted in a significant decrease of the passive resistive torque, but no change in Achilles tendon stiffness. In contrast, ballistic stretching had no significant effect on the passive resistive torque of the plantar flexors. However, a significant decrease in stiffness of the Achilles tendon was observed in the ballistic stretch group.

Conclusion: These findings provide evidence that static and ballistic stretching have different effects on passive resistive torque and tendon stiffness and both types of stretching should be considered for training and rehabilitation programmes.

KEY WORDS

Flexibility, muscle, tendon, stiffness

INTRODUCTION

It is controversial whether stretching promotes better performances and decreases the number of injuries (34). However, stretching exercises are regularly included in warm – up and cooling – down activities. On the sports field, the two most commonly used stretching techniques are static and ballistic stretching. Static stretching involves a slow, controlled lengthening of a relaxed muscle (1). A ballistic stretch is a bouncing rhythmic motion and uses the momentum of a swinging body segment to lengthen the muscle. Guissard et al. (11) reported that ballistic stretching caused the facilitation of the stretch reflex, which is mediated by the facilitatory influences of muscle spindles type Ia and II receptors upon homonymous alpha motor neuron excitability. This activation of the stretch reflex causes a contraction in the muscle being stretched. Thus, it has been stated that ballistic stretching is disadvantageous for improving range of motion, and perhaps even harmful because the muscle may reflexively contract if restretched quickly and create injury to the muscle fibres (30).

Many studies have attempted to determine whether outcomes such as range of motion or task performance are different depending upon the type of stretching undertaken. Sady et al. compared ballistic, static and proprioceptive neuromuscular facilitation (PNF) and showed that all techniques were able to improve range of motion but PNF was seen as the preferred technique (29). Similarly, Lucas and Koslow also concluded that all three techniques were able to increase flexibility after a training period of seven weeks (19). Wallin et al. compared the effects of a modified contract – relax method and a traditional ballistic stretch method (33). These authors showed that the contract – relax method was significantly better than the ballistic stretch method for improving range of motion. More recently some authors have examined the effects of stretching on performance in tasks. For instance, Woolstenhulme et al. determined the effects of four different warm – up protocols (ballistic stretching, static stretching, sprinting and basketball shooting (control group)) on range of motion and vertical jump height in basketball players (35). The findings showed that the ballistic stretch group had the greatest increase in range of motion. However, vertical jump height was not different after six weeks in any of the groups. More recently, Unick et al. also found no significant difference in vertical jump performance following either static or ballistic stretching (31).

Most previous work has focused their outcome upon range of motion. However, dynamometers have allowed the measurement of passive resistive torque associated with the range of motion changes (21,23,24). Furthermore dynamometer mesurements, combined with ultrasonography (7,15,16,17,25) have allowed the appreciation of stretch within tendon structures. To date, no studies have used these techniques to examine whether ballistic or static stretching have different effects upon measurements of passive resistive torque and stiffness. Theoretically, the rhythmical bouncing of ballistic stretching has different temporal characteristics in the applied forces, (eg: rate of application of force), compared to the sustained and steady force involved in a static stretch. As such, it might be expected that the contractile elements together with the serial and parallel elements within the muscle might over time respond differently to these types of stretch.

Therefore, the objective of the present study was to investigate if a static and ballistic stretching program had different effects on passive resistive torque measured during isokinetic passive motion of the ankle joint, and tendon stiffness measured by ultrasound imaging.

MATERIALS AND METHODS

Experimental Design

A randomised controlled pretest – posttest trial was utilised to assess two common stretching techniques during a 6 week training program. Ninety-six volunteers were prepared to take part in the study. The subjects were randomly assigned into three groups: a static stretch group (n = 33), a ballistic stretch group (n = 33) and a control group (n = 30). Randomization was performed independently. Thirty cards for the control group and 33 cards for both stretching regimes were shuffled in a container. After completion of all pre – intervention assessments, each subject picked one card in a blinded manner. Both stretching groups performed a stretching program with a duration of six weeks. They were asked to stretch their calf muscles every day. In order to supervise their training program, each person had to complete a personalized calendar of their stretching activity and was contacted every week by one of the investigators. The control group did not receive a training program. In order to supervise this group, the participants were contacted every week and were asked to complete a questionnaire at the end of the study. The main goal of this questionnaire was to make to sure that the subjects of the control group did not undertake additional stretching exercises over the intervention period. Unsatisfactory compliance with the prescribed regimes resulted in exclusion from the study. Before and after the six weeks of stretching, all subjects were evaluated for ankle range of motion, passive resistive torque of the plantar flexors and the stiffness of the Achilles tendon.

Subjects

The Ethical Committee of the Ghent University Hospital approved the study, and each participant gave a written informed consent prior to participating. Subjects were informed that the study was for research purposes and were encouraged to give maximal effort throughout the entire testing procedure. Subjects with a history of lower leg injuries were excluded from the study. Only recreational athletes were included in the study, competitive elite athletes were excluded. The personal stretching habits beyond the scope of the study protocol were questioned. During the study, all subjects were asked to maintain normal activity. The anthropometric characteristics of the subjects are presented in Table 1.

Table 1: The anthropometric characteristics of the 81 subjects

	Static Stretch Group (n = 31)	Ballistic Stretch Group (n = 21)	Control Group (n = 29)
Sex (M/F)	21/10	8/13	8/21
Age (years ± SD)	22.03 ± 1.11	21.90 ± 1.73	22.31 ± 1.91
Height (cm ± SD)	174.85 ± 7.71	177.33 ± 8.87	171.41 ± 8.44
Weight (kg ± SD)	67.71 ± 9.38	68.69 ± 9.83	64.78 ± 11.09

SD = standard deviation; n = number

Measures

Questionnaire

Prior to testing, all subjects completed a questionnaire to assess their medical history, their physical activity and their experience with stretching. In order to assess possible changes in their lifestyle and to detect the presence of injuries during the six weeks of training, this questionnaire was completed again after the six weeks of training. This was done in order to verify the compliance of each subject. The results of the questionnaires indicated that one person of the control group did additional stretching exercises, eight persons did not complete the stretching program successfully and 6 persons became sick or injured during the intervention period. Consequently, eighty-one of the 96 volunteers were included in the statistical analysis (37 males, 44 females) (static n = 31; ballistic n = 21; control n = 29).

Range of Motion Measurement

Dorsiflexion range of motion was measured with a universal goniometer (accurate to one degree) by the same investigator to provide good intra – rater reliability. This person did not know the group allocation of the subjects. Previous research using radiography has established the validity of goniometric measurements (10). Each measurement was repeated three times and the mean was used for statistical analyses. The left ankle was evaluated in a weight bearing position. The measurement was performed according to the method of Ekstrand et al. (5). The subject was standing upright with the feet parallel. The subject was asked to step back with the left foot and bring the ankle into maximum dorsiflexion, keeping the left knee straight and the heel on the ground. The subject was aware that the front leg must be flexed, the back leg must be kept straight and the feet must be facing forwards. The weight bearing measurement was also examined with the knee flexed (5). The subject was asked to stand on the floor with the left foot on a bench. Then, the subject was asked to lean forward in order to produce a maximal dorsiflexion in the left ankle, with the heel in contact with the bench and the knee maximally flexed. The bony landmarks used for these measurements were defined using the method of Elveru (6). The proximal arm of the universal goniometer was aligned with the head of the fibula. The axis of the goniometer was positioned 0.5 cm below the lateral malleolus. The distal arm was aligned parallel to an imaginary line joining the projected point of the heel and the base of the fifth metatarsal. This measurement has been found to be valid and reliable (5,6).

Passive Resistive Torque Measurement

For testing the passive resistive torque, a Biodex System® 3 isokinetic dynamometer was used. The subject was placed in a supine position with the knee maximally extended. The foot was securely strapped to a footplate connected to the lever arm of the dynamometer. The standard Biodex ankle unit attachment with the provided Velcro® straps was used. All subjects were asked to wear the same sport shoes with a low cut in both test sessions. The same investigator strapped the foot prior to and after the stretching period. The attachment of the foot was also such that the movement of the ankle joint was not impeded, in order to avoid an overestimation of the passive resistive torque. The height and the distance of the foot attachment was registered in order to make the assessment reproducible in the post test session. During the testing session, the dynamometer moved the ankle passively through 4 continuous cycles of motion between 20° plantar flexion to 10° dorsiflexion at 5°/ sec, with neutral being the line of the tibia perpendicular to the footplate. These range of motion limits were used in the pre-testing session and the post-testing session. This range of motion is used during many functional activities (3). A slow stretch speed was used in an attempt to ensure that the stretch did not elicit reflexive muscle activity. Most authors agree that 5°/sec achieves this purpose (9). The subjects were instructed to relax, and before data collection, each person performed a test trial to become familiar with the system. During the test session, electromyographic activity from the plantar and dorsiflexor muscles was recorded (MyoSystem 1400, Noraxon USA Inc., Scotssdale, AZ). Surface electrodes with an electrical surface contact of 1 cm^2 (Ag-AgCl, BlueSensor, Medicotest GmbH, Germany) were placed on the soleus, the tibialis anterior and the medial head of the gastrocnemius muscle according to the guidelines of Basmajian with an interelectrode distance of 10 mm (2). The EMG tracings were monitored during the tests in an effort to ensure that calf muscle activity was less than 0.05 mV above baseline during the passive stretch cycles (9). This EMG activity corresponds to approximately 2% MVC. The bandwidth of the frequency response was 20Hz to 4 kHz (9). Similar to Gajdosik et al., the raw EMG signals were relayed to an amplifier (x 5,000) and high pass filtered at 20Hz, and the analog signals were converted to digital data at a sampling rate of 500 Hz (9). The test was repeated if the subject was not relaxed sufficiently, i.e. if the muscle activity was higher than 0.05 mV. The peak passive resistance torque (N.m) recorded from the dynamometer over four cycles of motion was used in the statistical analysis. A pilot study demonstrated that the reproducibility was high (ICC = 0.93-0.94, $p < 0.001$).

Measurement of the passive stiffness of the Achilles tendon

The ratio of the calculated muscle force (F_m) and the elongation of the Achilles tendon (ELONG) provided a measure of the stiffness of the Achilles tendon. In respect to the muscle force, firstly, the measured torque TQ (N.m) during maximal isometric plantar flexion was converted to muscle force F_m (N) using the following equation:

$F_m = k. TQ. MA^{-1}$

Where k is the relative contribution of the physiological cross-sectional area of the medial gastrocnemius within plantar flexor muscles (18%) (8) and MA is the moment arm length of triceps surae muscle at 90° of ankle joint (50mm) (28,32). Therefore:

$F_m = 18/100 \, . \, TQ. \, (0.05)^{-1}$

Secondly, the ratio of F_m and ELONG provided the stiffness of the tendon (STIFFN, N/mm). In this study, the calculations were based upon those of Kubo (18). Both legs were tested. The test - retest reliability of measuring the stiffness of the Achilles tendon using ultrasonography has been shown to be good (ICC = 0.80-0.82) (22).

Measurement of the torque

The dynamometer (Biodex System 3®) was used to determine torque output during isometric plantar flexion. The subject lay prone on a bench. First, the left ankle was placed in a 90° position (anatomical position) with the knee joint at full extension and the foot securely strapped to a footplate connected to the lever arm of the dynamometer. The standard Biodex ankle unit attachment with the Biodex provided Velcro® straps was used in this study. In order to prevent ankle joint changes, the foot was firmly attached to the footplate of the dynamometer with a strap. The position and the height of the Biodex chair were also recorded for each subject individually and were used in the following evaluations. Before the test, the subjects performed 3-5 submaximal contractions to be accustomed to the test procedure. After this warm-up, the subjects were instructed to develop an isometric maximal voluntary contraction (MVC) during five seconds. The task was repeated three times per subject with 30 s rest between the trials. Visual examination was undertaken to ensure that the subject's ankle joint did not move during this muscle work. When motion was observed, the trial was discarded. Each subject was verbally encouraged to exert maximal voluntary effort by contracting as hard as possible. The maximal isometric strength was defined as the peak torque recorded. The force of the tendon was estimated from the plantar flexion torque, the physiological cross-sectional area ratio of the medial gastrocnemius to all the plantarflexors, and the moment arm (see formula above).

Measurement of elongation of the tendon

To obtain a measurement of the elongation of a tendon, the method of Fukashiro (7) was used. In the present study, a real-time ultrasonic apparatus (Siemens® Sonoline SL-1) was used to obtain a longitudinal ultrasonic image of the medial gastrocnemius (MG) muscle at

30 % of the lower leg (i.e. from the popliteal crease to the centre of the lateral malleolus (17). An electronic linear array probe of 7.5 MHz wave frequency was secured with Velcro® straps on the skin. The ultrasonic images were recorded on videotape (Digital Camera Sony®). One tester who was not aware of the group allocation of the subjects visually identified the echoes from the aponeurosis and the MG fascicles. Parallel echoes running diagonally represent the collagen-rich connective tissue between the fascicles of the medial gastrocnemius. The darker areas between the bands of echoes represent the fascicles. The echo that runs longitudinally in the middle is from the aponeurosis. The point (x) at which one fascicle was attached to the aponeurosis was visualised on the ultrasonic image. This point (x) moved proximally during isometric torque output. The distance travelled by x ($\triangle$x) is considered to indicate the lengthening of the aponeurosis and therefore also of the tendon (14,25). Measuring the displacement was done with the multimedia player, Light Alloy 1.D. The mean value of the three measurements was used as a representative value for the elongation of the tendon (ELONG).

Stretching program

The two stretching groups performed calf stretching exercises every day for an intervention period of six weeks. The exercises were comprised of a classical “standing wall push”, performed successively on both legs. The same information and instructions were given to each subject. For example, the subjects were instructed that the holding point of the stretch be at the point “just before discomfort”. The static stretch group was instructed to hold the back knee completely extended. The subjects in the ballistic stretching group followed an identical stretching protocol except once these subject had reached the initial stretching position, they were instructed to move up and down at a pace of one movement per second with the front knee. After four weeks, all subjects received a wedge to perform the stretching exercise. Hence, subjects could increase the stretching intensity. This wedge (with a height of 5.7 cm) was placed under the forefoot of the back leg. During each stretching session, the stretch was repeated five times at each leg. After performing the stretch for 20 seconds, the subject rested 20 seconds before that leg was stretched again. Each subject received an audio-CD with the stretch duration, the rest duration and the rhythm of the exercise in order to standardize the program as much as possible.

Statistical Analyses

Statistical analysis was performed with Statistical Package for the Social Sciences (version 11.0; SPSS Inc., Chicago, IL). The data were assessed for normality using the Kolmogorov – Smirnov test. One–way ANOVA's were used to compare the baseline characteristics of the three groups. To determine a significance of an interaction effect (time x group) or main effect for time, a General Linear Model for Repeated Measures (GLM) was performed. Gender and the pre – treatment measures were entered as covariates in the model. In these analyses, the Mauchly's test of Sphericity was significant, indicating that the assumption of sphericity had been violated. Therefore, a Greenhouse – Geisser correction factor was applied to all p–values. Pair–wise differences were examined using Bonferroni tests and the alpha level was set at 0.05 for all hypotheses.

RESULTS

Pretraining results

The left ankle of 81 subjects was included in the statistical analyses. No significant differences were observed between the three groups at baseline. The baseline characteristics of the three groups are presented in Table 2.

Table 2: The baseline characteristics of the three groups

	Static stretch group		Ballistic stretch group		Control group		*P*
	Mean	SD	Mean	SD	Mean	SD	
ROM ext (°)	28.06	6.50	28.76	6.79	28.00	5.21	0.896
ROM flex (°)	36.03	9.17	36.05	9.17	37.38	6.67	0.788
PRT (N.m)	17.99	3.76	17.99	4.47	17.12	3.81	0.641
STF (N/mm)	59.42	37.09	66.27	41.27	46.04	25.11	0.261

(ROM: dorsiflexion range of motion, ext: with the knee extended, flex: with the knee flexed, PRT: passive resistive torque of the plantar flexors, STF: passive stiffness of the Achilles tendon, SD: standard deviation, $\alpha = 0.05$)

Posttraining results

Range of motion

Table 3A and 3B show that both stretching groups had a significantly increased dorsiflexion ROM for both measurements, with the knee flexed and extended. The control group also showed a significant increase in dorsiflexion range of motion. There were no significant interaction effects.

Table 3A: The results of the GLM – model on the range of motion measurements of the left leg.

Group	Measurement	Pre		Post		Main effect time
		Mean (°)	SD	Mean (°)	SD	p < 0.000 Post hoc: p-value
Static	ROM ext	28.06	6.50	30.64	6.35	<0.001
	ROM flex	36.03	9.17	39.03	8.13	<0.001
Ballistic	ROM ext	28.76	6.80	32.00	7.29	0.001
	ROM flex	36.05	9.17	39.43	8.56	<0.001
Control	ROM ext	28.00	5.21	30.21	5.02	0.013
	ROM flex	37.38	6.68	39.24	6.36	0.001

(ROM: dorsiflexion range of motion, ext: with the knee extended, flex: with the knee flexed, SD: standard deviation, α = 0.05)

Table 3B: The results of the GLM – model on the range of motion measurements of the left leg, after covariate – adjustment.

Group	Measurement	Pre		Post		Main effect time
		Adjusted Mean (°)	Adjusted SD	Adjusted Mean (°)	Adjusted SD	p = 0.049 (ext) p < 0.001 (flex) Post hoc: p-value
Static	ROM ext	28.15	6.69	30.85	6.20	0.002
	ROM flex	36.12	8.87	39.23	7.65	0.002
Ballistic	ROM ext	28.21	6.92	31.89	6.67	0.001
	ROM flex	35.32	9.35	39.16	8.98	0.005
Control	ROM ext	28.25	5.48	29.83	5.10	0.009
	ROM flex	37.33	6.09	39.50	6.25	0.064

(ROM: dorsiflexion range of motion, ext: with the knee extended, flex: with the knee flexed, SD: standard deviation, covariates: gender and pre –treatment stiffness measures, α = 0.05)

Passive resistive torque

The results showed a significant main effect for time. Post hoc testing revealed that the PRT decreased significantly in the static stretch group after six weeks of stretching. The PRT of the ballistic stretch group and the control group was not changed significantly. There was no significant interaction effect. The results of these analyses are presented in Table 4A and 4B.

Table 4A: The results of the GLM – model on the passive resistive torque measurements of the left leg.

Group		Pre		Post		Main effect time p=0.017
		Mean (N.m)	SD	Mean (N.m)	SD	Post hoc: p-value
Static	PRT	17.99	3.77	16.61	3.30	0.040
Ballistic	PRT	17.99	4.48	17.86	4.49	0.609
Control	PRT	17.12	3.81	16.23	4.29	0.081

(PRT: passive resistive torque of the plantar flexors, SD: standard deviation, α = 0.05)

Table 4B: The results of the GLM – model on the passive resistive torque measurements of the left leg, after covariate – adjustment.

Group		Pre		Post		Main effect time p=0.005
		Adjusted Mean (N.m)	Adjusted SD	Adjusted Mean (N.m)	Adjusted SD	Post hoc: p-value
Static	PRT	17.65	3.43	16.39	3.28	0.026
Ballistic	PRT	17.94	4.55	18.25	4.49	0.863
Control	PRT	16.97	3.49	16.13	3.98	0.160

(PRT: passive resistive torque of the plantar flexors, SD: standard deviation, covariates: gender and pre – treatment stiffness measures, α = 0.05)

Passive stiffness of the Achilles tendon

There was a significant main effect for time. Post hoc testing revealed that the stiffness of the Achilles tendon decreased significantly in the ballistic stretch group. In the static stretch group and the control group, no significant changes were found after the six weeks of stretching. There was no significant interaction effect. Table 5A and 5B show these results.

Table 5A: The results of the GLM – model on the measurements of the passive stiffness of the left Achilles tendon.

Group		Pre		Post		Main effect time p = 0.007
		Mean (N/mm)	SD	Mean (N/mm)	SD	Post hoc: p-value
Static	STF	59.42	37.09	53.40	24.52	0.231
Ballistic	STF	66.27	41.27	48.56	29.66	0.008
Control	STF	46.04	25.11	45.03	21.33	0.100

(STF: passive stiffness of the Achilles tendon, SD: standard deviation, α = 0.05)

Table 5B: The results of the GLM – model on the measurements of the passive stiffness of the left Achilles tendon, after covariate – adjustment.

Group		Pre		Post		Main effect time
		Adjusted Mean (N/mm)	Adjusted SD	Adjusted Mean (N/mm)	Adjusted SD	$p < 0.001$ Post hoc: p-value
Static	STF	53.13	29.11	54.75	24.79	0.812
Ballistic	STF	65.83	42.65	47.53	31.28	0.022
Control	STF	46.75	27.30	46.24	23.20	0.942

(STF: passive stiffness of the Achilles tendon, SD: standard deviation, covariates: gender and pre-treatment measures, $\alpha = 0.05$)

DISCUSSION

The results of the study revealed that dorsiflexion range of motion was increased significantly in all groups. Previous studies, using goniometry confirm that joint range of motion can be increased by stretching (27,29). In order to assess the effects of static and ballistic stretching more completely, resistive torque during passive motion was examined together with the stiffness of the Achilles tendon.

The results related to the passive resistive torque show that after six weeks of stretching, it was significantly decreased albeit by a relatively small amount in the static stretch group, and remained unchanged in the ballistic stretch group. The finding related to the static stretching group was in agreement with some previous studies (16), but not all (21,27). Where no change has been observed, authors generally argue that the viscoelastic parameters have not been altered, and changes in torque and range of motion have occurred due to increased stretch tolerance. Since the range of motion in which the passive resistive torque was measured was the same in the pre – and post testing, the small but significant decrease in passive resistive torque observed in the static stretch group has to be due to structural changes (21). While it is beyond the methods of the current study to define what structures changed, the most commonly reported would be an increase in sarcomeres (4,9,26). Indeed, Coutinho et al. investigated the effect of passive stretching applied every 3 days to the soleus muscle of rats and found an increase in serial sarcomere number over a three week period (4). Interestingly, in the current study, no change was observed with ballistic stretching which might indicate that the tension placed on the muscle should be continuous and not intermittent as would have been occcuring with the ballistic techniques used in the current study. Alternatively, it may be that the forces generated in the range of motion tested did not elicit or show the effects of ballistic stretching.

In the present study we observed no significant changes in tendon stiffness after six weeks of static stretching. In contrast, after six weeks of ballistic stretching, the stiffness of the Achilles tendon decreased significantly. Only one previous study has examined the effects of a stretching programme on tendon stiffness in vivo. In that study, Kubo et al. (16) investigated the effects of a 3 week static stretching program, and found that tendon stiffness was unchanged, a finding in agreement with the current study. Why these different responses occurred is not clear, but may be related to the effect of stretching on the contractile elements versus the tendon. While the resting contractile elements have been shown to be more compliant than tendon for a particular length, the much greater length of tendon attached to the plantarflexor muscles in-vivo means that when these muscles are stretched, much greater strains are observed in the tendon compared to the contractile elements (12). It may be that these larger strains induce an adaptation in the collagen fibres within the tendon, and this adaptation may require a repetitive changing stimulus (applied force) such as seen in ballistic stretching as compared to the sustained steady force associated with static stretching.

Another possible mechanism for the different effect of static and ballistic stretching on tendon stiffness is related to the viscosity of the muscle tendon complex. Recently McNair et al. (23) reported that stiffness was decreased significantly more during cyclic motion compared to static stretching within a single stretching session, and these authors speculated that the more mobile constituents of soft tissues such as the polysaccharides and water are redistributed within the collagen framework more rapidly during cyclic motion. In this respect, Hutton (13) has commented that muscles display thixotropic behaviour, a rheological term related to the viscosity of a gel and resistance to molecular deformation, and that motion leads to a decrease in the viscosity of the system. It may be that there are perennial changes in the viscosity of the system as a result of longer term stretching affecting the composition of these components.

In respect to the findings, it should be kept in mind that the passive resistive torque and the measures of Achilles tendon stiffness cannot be compared directly, primarily due to the extremely different forces associated with these tests. In the range of motion that passive resistive torque was measured, the forces are many times less than those associated with a maximum effort activation of the plantar-flexor muscles. There were also some limitations to the methodology of the present study. First of all, the position at which the isometric contraction was undertaken was 90 degrees (anatomical position), and it was assumed that there was zero strain in the tendon at this point. However, Muramatsu et al. (25) have shown that this is not so and hence the amount of displacement in the tendon will be underestimated and the subsequent measurement of stiffness would be overestimated. That said, Figure 8 in their paper shows that the effect upon strain between 10-90% MVC is relatively small. The ramifications in respect to measurements before and after stretching is that any decrease in stiffness might be overestimated. In respect to the calculation of F_m, we used the same moment arm for all our subjects, a technique used by others (8,14,16,17,18). For the measurement of individual moment arms, either direct measurements by MRI using the Reuleaux method as previously described (20,22); or by indirect measurement involving the calculation of the ratio of change in tendon length to change in joint rotation would be required. Similarly, individual measurements of k which is the relative contribution of the physiological cross-sectional area of the medial gastrocnemius within plantar flexor muscles would be more accurately assessed by MRI. It should also be noted that although tendon displacement changes were measured during "isometric" muscle activation, it has been shown that small amounts of ankle joint rotation (3-7 degrees) can take place, and these can markedly affect the displacement measurements, particularly at high levels of a MVC leading to an overestimation of displacement and hence an underestimation of stiffness (21,25). In the present study, we looked for these joint motion changes, but only by visual observation, and if they were observed, then those data were discarded and the test repeated. Finally, why there was an increase in ROM in the control group should be considered. In this regard, as the responses to the questionnaires of the control group subjects indicated that they had undertaken no additional stretching exercise over the intervention period, we believe the observed changes represent a learning effect. That is, at the second testing session, the subjects were able to undertake the ROM test with greater skill as a result of the practice they had received in the baseline testing session.

In summary, in the present study static stretching resulted in a small decrease of the passive resistive torque in combination with no change in tendon stiffness. In contrast, ballistic stretching had no significant effect on the passive resistive torque. However, a decrease in stiffness of the Achilles tendon was observed after ballistic stretching. These findings have implications for the prevention of injury and for performance. They indicate that a combination of ballistic motion and holds may be most appropriate for training and rehabilitation programs.

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CHAPTER 6

GENERAL DISCUSSION

GENERAL DISCUSSION

The first aim of this dissertation was to gain a better insight into the intrinsic risk factors for the development of an Achilles tendinopathy. Secondly we wanted to investigate which regimes could be used in prevention and rehabilitation programs. Therefore, this chapter focuses on the possible risk factors for the development of an Achilles tendinopathy and the derived appropriate prevention and rehabilitation programs. The strengths and limitations of this dissertation and directions for future research will complete this chapter.

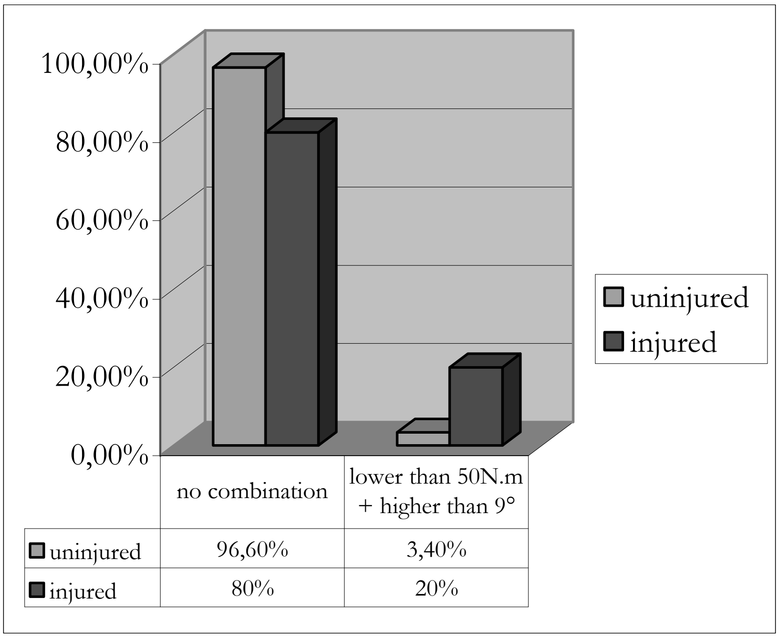
Although Achilles tendinopathy is frequently encountered in the sports injury clinic, its risk factors remain obscure. As outlined in the general introduction, various extrinsic risk factors have already been clearly recognized: changes in training patterns, poor technique, previous injuries, footwear and environmental factors. However, the relationship between the intrinsic risk factors and the occurrence of an Achilles tendinopathy is still obscure.

In **chapter 3** of this dissertation, a prospective study in male military recruits was set up to obtain a better insight in possible mechanical intrinsic risk factors. Sixty – nine male officer cadets followed the same 6-week basic military training. Before this training, each subject was evaluated for anthropometrical characteristics, isokinetic muscle strength, ankle joint range of motion, Achilles tendon stiffness, explosive strength, and leisure and sports activity. Ten of the 69 male officer recruits (14.5%) sustained an Achilles tendinopathy. Because all recruits followed the same training program with the same equipment, environmental conditions, food, and daily schedule, the impact of the extrinsic risk factors was kept to a minimum.

The anthropometrical characteristics of the recruits, their level of physical activity nor their explosive strength were identified as predisposing factors for the development of an Achilles tendinopathy. Neither was the stiffness of the Achilles tendon seen as an intrinsic risk factor for an Achilles tendinopathy. In **chapter 3**, the ultrasonic measurement technique described by Fukashiro et al. (11) was used to identify tendon stiffness. During isometric contractions of the plantar flexors, the lengthening of the tendon and the aponeurosis was observed. The relationship between the supplied muscle force and the elongation of the Achilles tendon was calculated to obtain a measurement of the tendon stiffness. The test – retest reliability of this technique was investigated in **chapter 2** of this dissertation. Twenty – one healthy men and women took part in the study. The subjects underwent three identical test sessions held seven days apart. The Intraclass Correlation Coefficient for the stiffness of the right and the left Achilles tendon was 0.80 and 0.82 respectively. These results demonstrate that this technique is reliable for the evaluation of the elastic properties of the Achilles tendon. It is a clinically useful tool for the assessment of tendon properties.

Unlike the above parameters, the results of **chapter 3** do reveal that the male recruits with lower isokinetic plantar flexor strength and increased dorsiflexion excursion were at a greater risk for developing an Achilles tendon overuse injury. These findings shaped the subsequent development of this dissertation. One chapter concerns a strengthening program and the other chapter concerns a stretching program. An important remark should be made. In **chapter 3** significant differences in plantar flexor strength could be found between the injured and the uninjured recruits. Moreover, a decreased plantar flexor strength was found to be a risk factor for the development of an Achilles tendinopathy. In contrast, no significant differences in range of motion could be found between the injured and the uninjured recruits. Therefore, it could be questioned why an increased dorsiflexion range of motion was still indicated as a risk factor for an Achilles tendinopathy. Moreover, in the literature, a decreased range of motion was indicated to be correlated with an overuse injury (15,18). Making an attempt to clarify this 'statistical oddity' we believe that the combination of a decreased plantar flexor strength and an increased dorsiflexion range of motion seems to be a risk factor for the development of an Achilles tendinopathy. Figure 1 shows that 20% (2/10) of the injured persons had a combination of a decreased plantar flexor strength and an increased dorsiflexion range of motion. However, these preliminary results should be confirmed by further research.

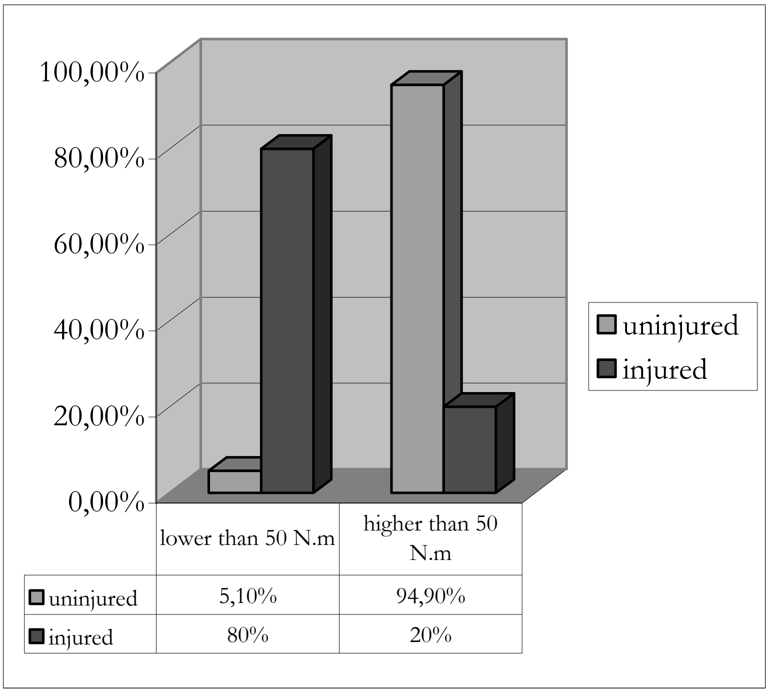
Figure 1 shows how many of the recruits who developed an Achilles tendinopathy had a combination of a plantar flexor strength lower than 50.0 N.m and a dorsiflexion range of motion higher than 9°.



Decreased plantar flexor strength was identified as an intrinsic risk factor for the development of an Achilles tendinopathy

One of the most striking findings of the prospective study **(chapter 3)** was that the isokinetic strength of the plantar flexors was identified as a predictor for an Achilles tendinopathy. Subjects with a plantar flexor strength lower than 50.0 N.m in our study were predisposed to an Achilles tendinopathy. Figure 2 shows how many of the persons who developed an Achilles tendinopathy had a plantar flexor strength lower than 50.0 N.m. Presumably, greater muscle strength produces stronger tendons that could deal better with high loads. During daily and sports activities, the muscle – tendon unit is exposed to many stretch – shortening cycles. During these cycles, the muscle – tendon must be able to absorb high forces. Several previous studies have suggested muscle strength to be a risk factor for an ankle injury in general (3,9,43). However, this is the first study that investigates the relationship between the strength of the plantar flexors and an Achilles tendinopathy in a prospective manner.

Figure 2 shows how many of the persons who developed an Achilles tendinopathy had a plantar flexor strength lower than 50.0 N.m.



Consequently, because a strength deficit of the plantar flexors was identified as a risk factor for the development of an Achilles tendinopathy, strengthening the calf muscles must definitely be a cornerstone in prevention and rehabilitation programs. In the literature, several intervention programs have shown to be effective to increase muscle strength. Isokinetic training programs, eccentric and plyometric training programs are able to increase the strength of the calf muscles (1, 31). All of these modalities are well provided with evidence - based research. Some other, relatively new modalities, lack scientific evidence. One of these methods is vibration training. Because the effect of whole-body vibration on muscle strength and explosive power are questioned in the current literature, we found it interesting and clinically relevant to investigate these effects of whole-body vibration in **chapter 4**. Moreover, it was shown in the literature that the injured side of a patient with Achilles tendinopathy had a significantly lower muscle calf strength compared to the uninjured side (2). Therefore, new technologies in strength training can provide new possibilities for prevention and rehabilitation of an Achilles tendinopathy.

In addition, whole-body vibration is used in daily practice for different other reasons. For example, it is still unclear if vibration training has an effect on the postural control of both healthy persons and patients (29,40,44,45). That is why also the effect of whole – body vibration on postural control was investigated in **chapter 4**. Because this parameter does not directly correlate with the subject of this dissertation, it will not be further discussed in this section.

In **chapter 4**, the supplemental value of a whole - body vibration program in comparison to an equivalent traditional resistance program was investigated. Thirty – three competitive skiers were randomly divided into a whole - body vibration group and an equivalent resistance group. Prior to the start of the study, as well as after the six weeks of training, all subjects were evaluated for isokinetic plantar and dorsiflexion strength, isokinetic knee flexion and extension strength and explosive strength.

The results of the study showed that both the whole - body vibration program and the equivalent resistance training program improved the isokinetic ankle and knee muscle strength, and the explosive strength of the subjects after the training period. These findings were in accordance with those of several authors, affirming that whole - body vibration increases the dynamic strength of the lower extremity muscles (5,10,37,44). However, there is only one study with the same study design, i.e. using the same exercises on the vibration platform and on the ground in both intervention groups. This study design was choosen in order to detect the supplemental value of vibration training. Ronnestad (39) concluded that there was a trend toward better results in maximal strength and explosive power for the squats performed on a vibration platform. Correspondingly, the results of our study revealed that the gains in explosive strength and in plantar flexor strength at low speed were significantly higher in the whole - body vibration group after six weeks of training. For all other parameters there were no significant differences between the change scores of the whole-body vibration group and the equivalent traditional resistance training group. As a result, it can be concluded that the training effects of vibration training are quite similar to a traditional training program for most of the strengthening parameters. Further studies should be executed in order to define the real supplemental value of whole – body vibration concerning explosive strength.

Besides the occurrence of the "tonic vibration reflex" (38), it has been proposed that the recruitment thresholds of the motor units during whole - body vibration are lower than during voluntary muscle contractions. This results probably in a more rapid activation and training of high- threshold motor units (36). Therefore, it has been suggested that vibration training specifically trains fast-twitch fibers, which are responsible for explosive power. Strangely enough, in **chapter 4**, there was a gain in explosive strength and in plantar flexor strength at low speed. Based on the occurrence of the "tonic vibration reflex", it is remarkable that no gain was found in plantar flexor strength, measured at high speed. We have no explanation for this finding. It is possible that the isokinetic test at a speed of 120°. s^{-1} was not 'fast' enough to detect possible changes in the fast – twitch fibers. Maybe an isokinetic test at even a higher speed would be more appropriate.

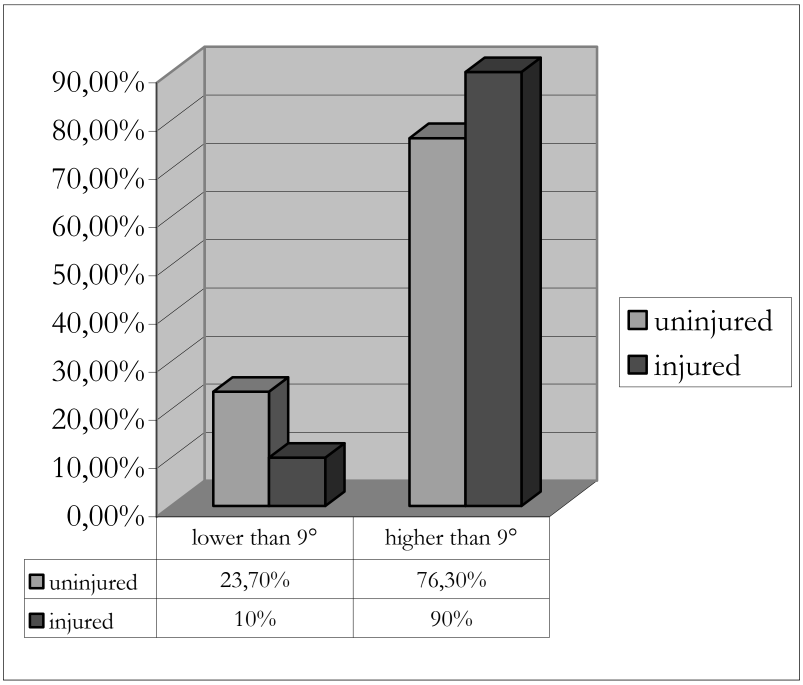
It could also be questioned why the best results were found in the plantar flexor muscles. It is known in literature that the muscles in a stretched position are stimulated the most on a vibration platform (12,23). That could be an explanation for the fact that the plantar flexor muscles show better results that the dorsiflexor muscles. Secondly, the effect was also greater in the calf muscles in comparison to knee joint muscles. A plausible explanation is probably the closer position of the calf muscles to the vibration source.

Because the incidence of Achilles tendinopathy is high in explosive sport types (18) and because decreased calf muscle strength was identified as a risk factor we believe that vibration training can be an interesting additional tool in the prevention and rehabilitation of an Achilles tendinopathy. For example, exercises on the vibration plate could be presented to the athlete or the patient in order to change the training stimulus.

Greater dorsiflexion excursion was identified as an intrinsic risk factor for the development of an Achilles tendinopathy

In the prospective study of **chapter 3**, an increased dorsiflexion range of motion was also identified as a risk factor for an Achilles tendon overuse injury. Recruits with a significantly higher dorsiflexion range of motion had a significant greater risk of developing an Achilles tendinopathy. The calculated threshold was a dorsiflexion range of motion of 9.0 degrees. Figure 3 shows how many of recruits who developed an Achilles tendinopathy had a dorsiflexion range of motion higher than 9°.

Figure 3 shows how many of the military recruits who developed an Achilles tendinopathy had a dorsiflexion excursion higher than 9°.



However, when looking at the literature, the relationship between range of motion and lower extremity injury remains controversial. In a review by Murphy et al. (32), three studies reported an association between an increased range of motion and lower extremity injury, whereas four studies reported no association. Other studies even mention a decreased range of motion as a possible risk factor for a musculoskeletal injury (50). A possible reason for the disagreement in literature is that most studies investigated lower extremity injuries as a group and did not focus on a specific pathology.

Another reason is that the combination of a decreased muscle strength and an altered dorsiflexion mobility in our study is probably the worst case scenario for the development of an Achilles tendinopathy (Figure 1). If the same person already has a lower plantar flexor strength, the altered joint mobility only making him/her more suspectible for the development of an Achilles tendinopathy. Therefore, a good balance between muscle strength and joint mobility seems important.

Despite the inconsistency in the literature concerning range of motion and Achilles tendon problems, stretching is common practice in the prevention and the rehabilitation of

patients with an Achilles tendinopathy. However, it has to be noticed that the preventive character of stretching is still discussed in literature (51).
On the sports field the most commonly used stretching techniques are static and ballistic stretching. Many authors have tried to define the real value of the different stretching techniques (22,41,46). Most authors (22,25,28,41,46,48) agree that both stretching techniques can improve joint range of motion. However, it has not yet been clarified whether these different stretching techniques have different effects on the muscle – tendon tissue properties. Therefore, the objective of **chapter 5** was to investigate if static and ballistic stretching program had different effects on passive resistive torque measured during isokinetic passive motion of the ankle joint and tendon stiffness measured by ultrasound imaging.

Eighty – one healthy subjects were randomised into three groups: a static stretch group, a ballistic stretch group and a control group. Before and after the intervention period, all subjects were evaluated for ankle range of motion, passive resistive torque of the plantar flexors and passive stiffness of the Achilles tendon.

The results of the study revealed that dorsiflexion range of motion was significantly increased in all groups. The passive resistive torque of the plantar flexors decreased significantly in the static stretch group and remained unchanged in the ballistic stretch group. It is stated in literature that this decrease has to be due to structural changes within the muscle – tendon unit (25). While it was beyond the methods of the study in **chapter 5** to define which structures changed, the most likely would be an increase in sarcomeres.

No significant changes were observed in tendon stiffness after six weeks of static stretching. In contrast, after six weeks of ballistic stretching the stiffness of the Achilles tendon decreased significantly. Why these different responses occur is not clear, but it may be related to the effect of stretching on the contractile elements versus the tendon. While the resting contractile elements have been shown to be more compliant than tendon for a particular length, the much greater length of the tendon attached to the plantarflexor muscle in – vivo means that when these muscles are stretched, much greater strains are observed in the tendon compared to the contractile elements. It may be that these larger

strains induce an adaptation in collagen fibers within the tendon, and this adaptation may require a repetitive changing stimulus.
The viscosity of muscle-tendon complex is another possible explanation for the different effects of static and ballistic stretching on tendon stiffness. McNair et al. (28) reported that stiffness was decreased significantly more during cyclic motion compared to static stretching within a single stretching session. These authors speculate that the more mobile constituents of soft tissues such as polysaccharides and water are redistributed within the collagen framework more rapidly during cyclic motion. The results of **chapter 5** suggest that static stretching possibly has a greater impact on the structures within the muscle compared to those of the tendon.

Therefore, ballistic stretching might have a greater effect on the tendon tissue structures and can therefore be used when our goal is reducing the tendon stiffness. A combination of ballistic motion and static stretching is probably the most appropiate when "warming up" for many activities. However, this hypothesis should be confirmed by future studies.

Strengths and limitations of the studies

Establishing the reliability of a technique is an essential prerequisite for its implementation as a clinical tool. Therefore, **chapter 2** investigates the test – retest reliability of measuring the stiffness of the Achilles tendon. The most important benefits of the technique are that the measurement can take place in vivo and that the technique is non-invasive. However, some careful considerations need to be made. First, since the technique is based on the displacement of intramuscular fascicular structures that can be observed on the ultrasound image, the resulting deformation does not represent that of the muscle-tendon unit per se, but rather the total deformation of the combined tendon and aponeurosis (tendon structures) distal to the measurement site. Second, in order to calculate F_m the same moment arm and relative contribution of the medial gastrocnemius was used for all the subjects, despite variations among subjects. To determine the individual moment arm, sagittal plane MRIs should be obtained with the ankle in neutral position using the Reuleaux method (24,26). Also the relative contribution of the physiological cross – sectional area of the medial gastrocnemius within the plantar flexors should be determined individually in further research. Third, although ultrasonography is applied during "isometric" conditions, it has been shown that the very slight ankle rotation which is likely to take place, could markedly affect the displacement measurements. Also the two dimensional movement on ultrasonography could be seen as limitation of the study. Despite these limitations, the ability to measure the stiffness of a human tendon implies that several intervention programs designed to alter the stiffness can be evaluated and compared.

Chapter 3 is the first prospective study on the aetiology of an Achilles tendinopathy. The well – conducted design, the study population and the adequate definition of an Achilles tendinopathy are the strengths of the study. The influence of extrinsic risk factors was minimized because all military recruits followed the same military training in the same conditions, with the same equipment. Also the proper statistical analysis adds to the value of the study. It is the first study defining possible cutoff values for the obtained risk factors. However, there are also some limitations of the study. A limitation that will always be present in injury epidemiological research is the fact that not all contributing factors can be measured. The selection of the investigated potential risk factors was based on possible associations between observed variables and the injury showed in previous retrospective studies. The methods used to measure these variables were selected according to the reliability of the procedures and the availability of the equipment. In addition, it must be mentioned that other intrinsic risk factors can also, and probably will play a significant role in the aetiology. One of these factors are biomechanical 'abnormalities'. For example an increased foot pronation, a leg – length discrepancy and a decreased mobility of the subtalar joint have also been proposed as possible intrinsic risk factors for the development of an Achilles tendinopathy (8,13,14,18,19,27,33,34). Another limitation of the study is that the age of the subjects does not correspond with the peak age of athletes developing an Achilles tendinopathy. An Achilles tendinopathy is most often seen among subjects aged between 35 and 45 years (1), while the mean age of the military recruits was 18.41 years. Therefore, the extrapolation of our results to a general population must be performed with some caution In the future, the study should be repeated in an older population. A third limitation of the study is that the pathology was not controlled by the means of medical imaging. However, all injuries were registered and diagnosed by the same medical doctor. He used strict criteria based on history and symptoms of the injury, impaired performance and pain characteristics. Future research should take these limitations into account when setting up a new study design.

In **chapter 4**, the equivalent resistance training program consisted of exactly the same exercises as the whole - body vibration program. This advantage makes it possible to evaluate the supplemental value of whole - body vibration. It can be concluded that whole - body vibration training can be seen as a good 'substitute training method' to increase muscle strength. A limitation of the study was that no true control group was included. However, because all skiers were in preparation for the winter season, it was not possible to include a control group without any strength training. Another limitation of the study was that the duration of the training effects was not studied. A further limitation is that the most appropiate prescription for whole - body vibration are not known. The vibration amplitude and the frequency of the vibrations are very important in vibration training because they determine the load that the vibration imposes on the neuromuscular system during training. However, in previous studies, most attention was paid to the frequency of the vibrations (6,7). However, the results of our study demonstrated that the amplitude of the vibrations had some influence on the perceived exertion of the subjects. Secondly, the frequency was only increased in our population to 28 Hz because of the relatively young age of the skiers. Further studies should investigate the effects of a further increase of the vibration frequency.

Since general acceptance exists that dynamic training is more beneficial to neuromuscular development in athletes than isometric training, more studies should employ dynamic exercises on the vibration platform. If possible, the training should also be sport specific. Studies which investigate the effects of vibration training in patients with Achilles tendinopathy are lacking in current literature. Also the possible preventive character of whole – body vibration should be further investigated. Therefore, conclusions must be carefully interpreted when using whole - body vibration in rehabilitation programs and future research concerning this topic is certainly needed.

Because a greater dorsiflexion range of motion was identified as an intrinsic risk factor for an Achilles tendinopathy in **chapter 3**, it may be at first glance appear unusual to investigate the effect of two stretching techniques in **chapter 5**. However, the relationship

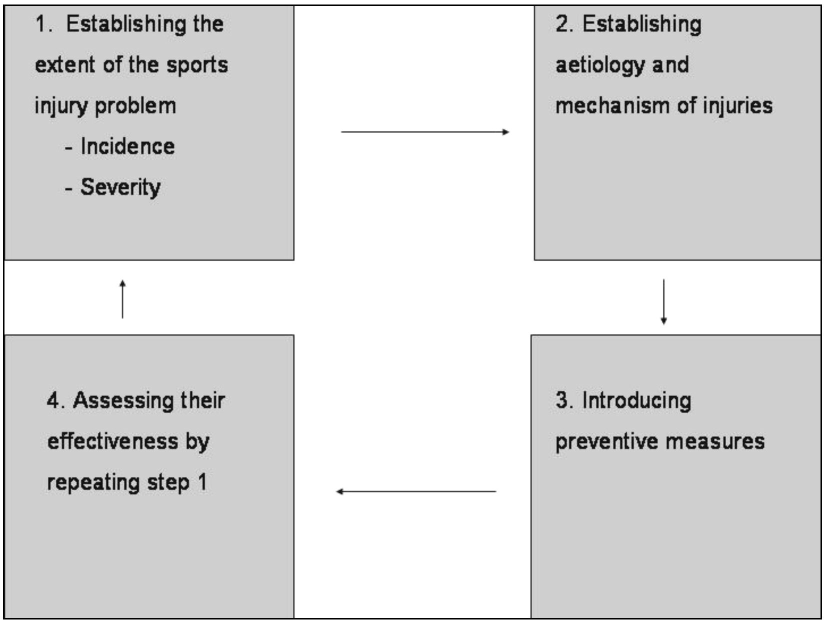
between an altered flexibility and injury is unclear in the literature and stretching is common practice in the rehabilitation of a tendinopathy.
Furthermore, the different effects of static and ballistic stretching on different tissue properties have not been investigated previously. Two relatively new methods were used in order to measure the passive resistive torque of the plantar flexors and the passive stiffness of the Achilles tendon. Future research should optimize these measurement techniques. It is hypothesized in **chapter 5** that static stretching causes structural changes, i.e. an increase in sarcomeres. However, this could not be concluded with certainty on the basis of the study procedures. Future studies using biopsy techniques should be executed.

An important limitation of all chapters in this dissertation, is that very different and specific study populations were examined. For example in **chapter 3** young military recruits were observed while in **chapter 4** young skiers were investigated. It has to be noticed that we have to be careful when extrapolating our results to a general population. The more so, as we know that the peak incidence of an Achilles tendinopathy is situated between age 35 and 45. On the other hand, sometimes it is necessary in a research study, to choose a clearly defined study sample. For example, the military population in **chapter 3** made it possible to control many possible risk factors which were not investigated.

Directions for future research

The aim of this dissertation was to obtain a better insight in the intrinsic risk factors for the development of an Achilles tendinopathy. It was also our purpose to highlight some possible prevention or rehabilitation programs. However, these aims do not exist in isolation but constitute as a part of a bigger entity. Van Mechelen et al. described this entity as a ‘sequence of prevention’ (Figure 4). A strategy of four stages in the sequence for the investigation of sports injuries was suggested (47).

Figure 4: The 'sequence of prevention' of sports injuries (47)



In this dissertation not all steps of the model were executed. Step 1 includes the identification of the magnitude of the problem. In **chapter 3**, a prospective epidemiological study in a very specific population was executed. In this study, we only focused on one specific injury, e.g. an Achilles tendon overuse injury. In future research, it would be interesting to study a more general population to get some more insight into the incidence of other injuries. For example, there could be a link between Achilles tendon injuries and other injuries (ankle sprains, fasciitis plantaris …). Secondly, not all possible intrinsic risk factors were investigated in **chapter 3**. It should be kept in mind that an Achilles tendinopathy is multifactorial and that probably other possible risk factors should be investigated in future research. As mentioned in step 3 of the model, preventive measures have to be introduced. In **chapter 4 and 5** of this dissertation, this was tried. However, step 4 reveals that intervention studies should be designed in order to examine if the proposed strategies really work. In future research, prospective studies of possible intervention programs (whole - body vibration, stretching, eccentric training) on the incidence of Achilles tendinopathy might reveal its real preventive value. Future studies should prescribe their training protocols in more detail, so that comparison between different studies becomes possible.

In earlier days, tendons were considered to be relatively non-vascular, inert and inelastic structures. It is only over the last decade that the dynamic nature of the extracellular matrix of tendon and skeletal muscle was appreciated. At his time, one believes that tendons are able to respond to mechanical forces by altering their structure, composition, and mechanical process. This process is called tissue mechanical adaptation or mechanotransduction (16,49). For example, Langberg et al. concluded that the blood flow within and around the Achilles tendon could increase three- to seven- fold with dynamic exercise (20). It has been shown that metabolic activity, the uptake of metabolic substrates and blood flow in the tendon are regulated in a specialized way that is independent of that occuring in skeletal muscle (17).

Moreover, collagen synthesis in human tendons rises with just one bout (60 min) of acute exercise, and the elevated collagen synthesis is still present 3 days after exercise (29). Langberg et al. investigated the effects of an eccentric heel drop program on the turnover of peritendinous connective tissue (21). They found that the collagen synthesis rate increased in the injured Achilles tendons.

It became clear that the amount of mechanical loading is very crucial in this process. For example, appropiate mechanical loading results in positive changes in tendons, whereas excessive loading leads to tendon degeneration. Therefore, further research studies should try to determine the most appropiate amount of mechanical loading, i.e. the border between too much or too little loading.

Like any other connective tissue, tendon does not undergo neovascularisation under normal conditions. As previously mentioned in this dissertation, this is the case in an Achilles tendinopathy. Boesen et al. concluded that eccentric exercise did not distinguish the flow during or after one training session in patients with chronic Achilles tendinopathy (4). They measured the immediate response after the eccentric exercise. These findings seem to be in contradiction with the long term effects of Öhberg et al (35). Future studies are needed to answer the question if exercise can have an effect on the neovascularisation.

Secondly, the exact characteristics of the mechanical loading are unknown. It has been shown in in vitro studies that cyclic mechanical stretching increases protein expression. Therefore, it might be hypothesized that cyclic loading with a stretching component is probably a trigger to start the mechanotransduction. Further studies should compare different types of mechanical loading (cyclic motions or holds, stretching or non – stretching) with different intensities in order to find out which modalities stimulate tendon regeneration the most. Once this is known, the existing intervention programs (eccentric training, whole-body vibration, ballistic stretching) should be compared with these optimal modalities. Knowing the most effective type and dose of mechanical loading is a prerequisite to improve prevention and rehabilitation programs for an Achilles tendinopathy.

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CHAPTER 7

NEDERLANDSTALIGE SAMENVATTING

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Een achillespeestendinopathie is één van de meest voorkomende peesletsels. Ondanks het frequent voorkomen blijft de aanpak van een achillespeesletsel dikwijls een bron van frustratie zowel voor de therapeut als voor de patiënt. Onduidelijkheid met betrekking tot de etiologie en het pijnmechanisme ligt hiervoor aan de basis.

In een *eerste luik* van dit werk was het de bedoeling om mechanische intrinsieke risicofactoren die kunnen leiden tot het ontstaan van een achillespeestendinopathie in kaart te brengen. Omdat er onduidelijkheid in de literatuur bestaat over mogelijke risicofactoren en omdat de meeste voorgaande studies op een retrospectieve basis gebeurden, werd in hoofdstuk 3 van dit werk een prospectieve studie opgezet. Negenenzestig mannelijke militaire recruten werden opgevolgd tijdens hun militaire training van zes weken. Voor de aanvang van de trainingsperiode, werden verschillende parameters bij de proefpersonen opgemeten, zoals hun lichaamskenmerken, de isokinetische kracht van de onderbeenspieren, de bewegingsuitslag van het enkelgewricht, de stijfheid van de achillespees, de explosieve kracht en hun activiteitenniveau. Tijdens de zes weken militaire training werden alle achillespeesletsels nauwkeurig geregistreerd. Tien van de 69 recruten ontwikkelden een achillespeestendinopathie. Uit statistische analyse bleek dat recruiten met een lagere isokinetische kuitspierkracht en een grotere dorsiflexiemobiliteit een groter risico hebben om een achillespeestendinopathie te ontwikkelen. Deze bevindingen bepaalden de verdere opbouw van de thesis.

De betrouwbaarheid van de methode om de stijfheid van de achillespees te bepalen (gebruikt in hoofstuk 3 en 5) werd nagegaan in hoofdstuk 2. Eenentwintig gezonde proefpersonen namen deel aan de betrouwbaarheidsstudie. De proefpersonen ondergingen drie identieke testsessies met telkens één week als testinterval. De intraclass correlatie coëfficiënt voor de stijfheid van de rechter en de linker achillespees was respectievelijk 0.80 en 0.82. Deze resultaten tonen aan dat de echografische methode een betrouwbaar middel is om de stijfheid van de achillespees te bepalen.

In een *tweede luik* van dit werk was het de bedoeling om een aantal programma's te evalueren die mogelijks gebruikt kunnen worden als behandelings- of preventiestrategie voor een achillespeestendinopathie.

Verschillende onderzoekers duiden op het belang van krachttraining binnen de aanpak van een achillespeestendinopathie. Vandaag de dag wordt het excentrisch oefenprogramma als 'gouden standaard' gezien binnen de revalidatie van een patiënt met een achillespeestendinopathie. Toch worden we vanuit commerciële hoek overstelpt met nieuwe, recentere alternatieven. Trainers en therapeuten wensen de waarde van deze 'hypes' te kennen om hun atleten en patiënten een zo breed mogelijk gamma aan krachttrainingsmiddelen te kunnen aanbieden. Eén van deze recentere alternatieven is triltraining of Whole-body vibration.

Whole-body vibration is een trainingsmethode waarbij het gehele lichaam aan trillingen wordt blootgesteld. De persoon neemt hiervoor plaats op een trilplaat. Mechanische vibraties, gekenmerkt door een richting, een amplitude, een snelheid en een frequentie, worden gegenereerd door de plaat. Recente onderzoeken toonden reeds aan dat triltraining leidt tot verschillende positieve effecten.

In hoofdstuk 4 van dit werk werd een studie opgezet om de meerwaarde van een trilprogramma na te gaan in vergelijking met een traditioneel krachtprogramma. Drieëndertig competitieve skiërs werden ingedeeld in een trilgroep en een gelijkwaardige krachtgroep. In beide groepen werden gedurende zes weken identiek dezelfde oefeningen uitgevoerd. De ene groep oefende op de plaat, de andere groep op de grond. Bij aanvang en na afloop van de interventieperiode, werden verschillende parameters opgemeten bij de proefpersonen. De isokinetische kracht van de onderbeen – en de bovenbeenspieren, de explosieve kracht en de posturale controle van de proefpersonen werden geregistreerd. De resultaten van de studie tonen aan dat zowel de triltraining als de gelijkwaardige krachttraining aanleiding geeft tot een significante verbetering van de isokinetische onderbeen - en bovenbeenspierkracht. Ook de explosieve kracht van de skiërs verbetert in beide groepen. Uit de analyse blijkt dat de toename in explosieve kracht en de toename in kuitspierkracht, gemeten aan lage snelheid, groter is in de trilgroep in vergelijking met de toename in de traditionele krachtgroep na zes weken training. Aangezien in hoofdstuk 3 is aangetoond dat een verminderde kuitspierkracht aanleiding kan geven tot het ontstaan van een achillespeestendinopathie, kan besloten worden dat Whole-body vibration als preventiemiddel kan worden aangewend. Verder prospectief onderzoek dient dit gegeven te bevestigen.

Stretching wordt algemeen aanvaard als een belangrijk onderdeel van een preventie - of revalidatieprogramma voor een achillespeestendinopathie. Op het sportveld zijn de twee meest gebruikte stretchingstechnieken het statisch en het ballistisch stretchen. Verscheidene auteurs hebben reeds in het verleden getracht om de werkelijke effecten van het stretchen na te gaan. De meeste onderzoekers zijn het erover eens dat beide stretchingstechnieken kunnen leiden tot een toename van de enkelmobiliteit. Het is echter nog niet duidelijk welke effecten het statisch en het ballistisch stretchen precies hebben op de verschillende spierpeeseigenschappen.

In hoofdstuk 5 werd het effect van het statisch en ballistisch stretchen op de passieve weerstand van de plantairflexoren en op de stijfheid van de achillespees met elkaar vergeleken. Eenentachtig gezonde proefpersonen werden gerandomiseerd in drie groepen: een statische stretchgroep, een ballistische stretchgroep en een controlegroep. Voor en na de interventieperiode van zes weken, werd de bewegingsuitslag van de enkel, de passieve weerstand van de plantairflexoren en de stijfheid van de achillespees opgemeten. De resultaten van de studie duiden aan dat de dorsiflexiemobiliteit toegenomen was in alle drie de groepen. De passieve weerstand van de plantairflexoren verminderde significant in de statische stretchgroep en bleef onveranderd in de ballistische stretchgroep en de controlegroep. In de literatuur wordt verondersteld dat deze afname in passieve weerstand te wijten zou zijn aan structurele veranderingen binnenin de spierpeeseenheid. Verder onderzoek dient te bevestigen dat een toename van het aantal sarcomeren in serie hier wellicht aan de basis ligt.
Er werd geen significante verandering aangetoond in de stijfheid van de achillespees na zes weken statisch stretchen. Wel blijkt uit de resultaten dat het ballistisch stretchen aanleiding gaf tot een significante daling in stijfheid van de achillespees. Mogelijks leidt het cyclisch karakter van het ballistisch stretchen tot een specifiek effect op de pees en minder op de spier. Het statisch stretchen, daarentegen, zou een groter effect vertonen op de structuren binnen de spier.

In dit werk werden twee mogelijke preventie – of revalidatieprogramma's voorgesteld. Verder prospectief onderzoek dient echter de werkelijke preventieve en therapeutische waarde van beide programma's te bevestigen. Tevens is het van het allergrootste belang dat de ideale modaliteiten voor dergelijke protocollen verder bestudeerd worden. Kennis omtrent het ideale type en de ideale dosis van trainingsbelasting is onontbeerlijk om preventie – en revalidatieprogramma's te optimaliseren.

In Greek mythology, Achilles was considered to be the bravest,
handsomest, and swiftest in the army of Agamemnon.
It is written that, his mother Thetis, dipped the child
in the waters of the river Styx, rendering him invulnerable
except for the part of his heel by which she had held him.
In the tenth year of the war with Troy, Achilles slew Hector.
The Aethiopis tells how Achilles was himself slain by Paris,
whose arrow guided to Achilles' heel by Apollo
(Homer, Iliad)