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A controlled intervention study assessing the relation between hip abductor strength and knee valgus

Master’s thesis in Human Movement Science

Trondheim, June 2015

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Abstract

Background: Anterior cruciate ligament (ACL) injury is a common and severe lower limb injury. Knee abduction moment has been associated with risk of non-contact ACL injury, and knee valgus angle has been reported as part of the non-contact ACL injury mechanism. Fatigued and weak hip abductors have been correlated with increased knee abduction moment and knee valgus angle. Strengthening the hip abductor muscles might play an important role in ACL injury prevention.

Purpose: To prospectively assess the relation between changes hip abductor strength and knee valgus and knee abduction moment.

Study Design: Controlled intervention study

Methods: 31 amateur female handball players with reduced knee control (mean±SD; age, 22.3±2.7 years; height 170.0±4.8 cm; weight, 72.6±8.3 kg) were divided into intervention (n=17) and control (n=14) groups. The intervention group performed a short-duration hip abductor resistance and sensorimotor control training program 2d/w for eight weeks in combination with their team training. Hip abductor strength was measured by handheld dynamometry at baseline, mid-protocol and post-test. Lower-limb kinetics and kinematics were calculated for the counter movement jump, in-jump landing and bilateral one-legged landing at baseline and post-test. Mixed design repeated measures analysis of variance (ANOVA) was performed to compare changes between groups.

Results: The intervention group did not significantly increase in hip abductor strength compared to the control group in any of the four strength tests ($p>0.05$). The intervention group significantly reduced their knee abduction moment compared to the control group in the take-off of the CMJ in the left ($F_{(1,21)}=4.4$, $p=0.05$, effect size (ES)=0.20) and the right leg ($F_{(1,21)}=4.9$, $p=0.041$, ES=0.22). Increased hip abductor strength was not related to reduced knee abduction moment and knee valgus angle when comparing players increasing in strength to players not increasing in strength in the intervention group ($p>0.05$).

Conclusion: Hip abductor strength increase was not related to reduced knee valgus. However, the intervention group did not significantly increase hip abductor strength compared to the control group. The hypothesis that increased hip abductor strength results in reduced knee valgus cannot be refuted, but this study could support the notion that solely focusing on strengthening the hip abductors is insufficient to reduce knee valgus.

Acknowledgements

In contributing to the work with this thesis, a great number of people deserve to be acknowledged. My counsellor Paul Jarle Mork has been a great discussion partner and given advice on the written work and design of this study, and I offer him great thanks. My second counsellor Gertjan Ettema have contributed greatly in the analysis of the knee joint dynamics of this study, and without him this study would have suffered greatly, and I offer him my greatest appreciation. Gunnvor Halmøy at the Norwegian Olympic Sports Centre, Region Mid-Norway has contributed in the design and screening in this study and has been of great help. Xiangchun Tan at NTNU Centre of Elite Sports Research has helped greatly with the setup in the laboratory. In general, staff and students at the NTNU Centre for Elite Sports Research and the Norwegian Olympic Sports Centre deserve recognition, as they have contributed as conversation partners or laboratory help. Perhaps most importantly, Eirik Nordgård Strupstad is owed great thanks. Without his organizing skills this study would likely have ended in a pile of unorganized paper and great despair. Coaches and players agreeing to participate in this study deserve great appreciation, as without them this study would not have been possible to conduct. Finally, all employees and students participating in the master program in Human Movement Science at NTNU have made these last two years well worth all the hours spent in the study hall or, even better, in front of Matlab program screen generously contributing to great highs and bottomless lows when analysing lower-limb dynamics. Thank you all!

Are Grytdal, May 2015

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1.0 Introduction

Physical activity and sport participation is in general considered health promoting for most people[1-5]. To reach or remain at a high level of performance, a substantial number of training hours need to be maintained over several months and years[6,7]. However, participating in sports increases the risk of injury[8,9], and the risk increases with level of play[10]. Suffering an injury can results in a loss of valuable training and competing hours[11], as well as pain and a loss of function[12] and eventually disability.

More than half of all sports injuries are to the lower limbs[8,11], wherein injuries to the ankle and knee are most common[8,13-15]. Injuries to the anterior cruciate ligament (ACL) are one of the more frequent acute lower limb injuries[16]. The ACL is the main ligament responsible for resisting anterior tibial translation relative to the femur and is also important for resisting tibial rotation relative to the femur[17,18]. The majority of ACL injuries in team sports occur in situations without direct contact with an opposing player[19,20]. The non-contact ACL injury situation usually involves a rapid weight-acceptance with a single knee close to full extension and in valgus[21-24], e.g., in plant and cut, turning, landing and faking movements[25-28]. In females, a knee in valgus is likely a more common characteristic of the non-contact ACL injury situation compared to in males[21,23]. Rupturing the ACL is a severe injury[12], and substantially increases the risk of early-onset osteoarthritis of the injured knee[29-31].

From 2005 to 2013 in Norway, females in the age group 15 to 19 years had an average annual primary ACL reconstruction rate of 161/100,000, more than twice as high compared to all older age groups. In males, the age group 20-24 years had the highest incidence of reconstructive surgery, at an average rate of 124/100,000[32,33]. In Norway it is estimated that half of all ACL injuries are reconstructed[34], indicating that the actual injury incidence rate is approximately double that of the primary reconstruction rate. Similar trends in age distribution are also found in the United States, where approximately 130,000 primary ACL reconstructive surgeries are performed annually[35] to an estimated annual cost of up to $7,6 billion[36]. The three sports with the highest total number of ACL reconstructive surgeries in Norway are, in descending order, the pivoting and high-impact sports soccer, handball and alpine skiing[34,37,38].

Females have up to six times higher non-contact ACL injury incidence rate compared to males in many team sports, including handball, volleyball and soccer[10,19,20,39,40], and female sports participation has increased substantially in recent decades[11]. In the top three divisions of Norwegian female handball, an ACL injury incidence rate of 0.2-0.6 injuries per team per season was found between 1998 and 2011[41]. Based on the number of teams playing on the top three levels in Norway[42], this is the equivalent of twenty to fifty Norwegian female top three-level handball players suffering an ACL injury each year since the late nineties.

Three main factors have been proposed to be responsible for the gender difference in non-contact ACL injury risk. Anatomical factors, such as a narrower femoral intercondylar notch[43] and hormonal factors such as high oestrogen levels during parts of the menstrual cycle affecting ligament laxity[44] could both be responsible for the higher non-contact ACL injury risk in females compared to males. Additionally, females demonstrate movement characteristics associated with a higher risk of non-contact ACL injury compared to males[45-48]. Neuromuscular factors such as strength and sensorimotor control affect segment alignments and body posture and thus the strain on the ACL[25,27]. These factors are modifiable[49,50] and are therefore of particular interest in an injury prevention perspective[27].

Altering movement pattern, technique, strength and sensorimotor control could be key factors in non-contact ACL injury prevention[25]. Injury prevention training programs have reduced the incidence[51-53] of and neuromuscular risk factors[54-57] for non-contact ACL injuries in females. Multi-component training programs likely yield more beneficial results compared to single-component programs[58-60], and compliance to the training program appears to be a key factor for successful effect of injury prevention training[51,61].

Knee abduction moment has prospectively been associated with an increased risk of non-contact ACL injury in adolescent females[62]. A knee abduction moment can increase ACL strain by increasing the compressive force on the lateral compartment of the knee joint and in this way cause internal rotation of the femur and anterior translation of the tibia relative to the femur[28]. The ACL will likely be subject to increased strain when forces act in the frontal, horizontal and sagittal plane simultaneously compared to when forces act only in one plane[26,28,63].

With knee abduction moment potentially being a key risk factor for non-contact ACL injury in females and the majority of non-contact ACL injuries in females occurring with a knee in valgus angle, the hip abductor muscles might play an important role in injury prevention. The hip abductor muscles resist hip adduction that in turn can lead to an increase in knee valgus angle and knee abduction moment[45,64].

Females demonstrate lower normalized hip abductor muscle strength compared with males[45,46,65,66], and low hip abductor muscle strength has been correlated with increased knee valgus angles and knee abduction moments[67-69]. Additionally, fatigued hip abductors have been associated with increases in knee valgus angle and knee abduction moment compared to non-fatigued hip abductors[70,71]. Increased hip abductor strength have prospectively been associated with reduced knee abduction moment in running[72] and landing[73]. Two studies[73,74] to date have prospectively investigated the relation between changes in hip strength and alterations in lower limb dynamics in jump tasks. One study[73] found significant effects of increased hip abductor strength on reduced knee valgus angle and knee abduction moment, while the second study[74] did not. However, the studies did not focus solely on hip abductor strength training[73-75] and one study[73] did not include a control group.

The aim of this study was to prospectively investigate the relation between changes in hip abductor muscle strength and changes in knee abduction moment and knee valgus angle in female handball players with reduced knee control. The hypothesis was that increased hip abductor strength would be associated with reduced knee valgus angle and knee abduction moment.

2.0 Methods

2.1 Study sample

Thirty-three female handball players with reduced knee control (mean±SD; age, 22.3±2.7 years; height, 170.0±4.8 cm; weight, 72.6±8.3 kg) volunteered to participate in the study. The players were assigned to either an intervention (INT, n=19) or control (CON, n=14) group. Players in the intervention group followed a hip abductor resistance and sensorimotor control training program 2d/w for eight weeks (see 3.4 below).

The players were recruited from teams mainly playing on the third and fourth highest level in the divisional system of Norwegian female handball, with some players competing on the highest (n=3) and fifth highest level (n=3), respectively. Figure 1 shows a flow chart of the number of teams and players eligible for inclusion and how many were excluded or did not wish to participate. The study was approved by the Regional Committee for Ethics in Medical Research (project no. 2014/1135) and all participants signed an informed consent before enrolment. The study was carried out according to the Declaration of Helsinki.

During the eight-week intervention period, two players in the intervention group resigned from participating in the study, due to reasons unrelated to the study or intervention training. A total of 31 players (INT n=17; CON n=14) met for post-testing, and were included in the data analysis. Characteristics of players participating in the study are presented in Table 1.

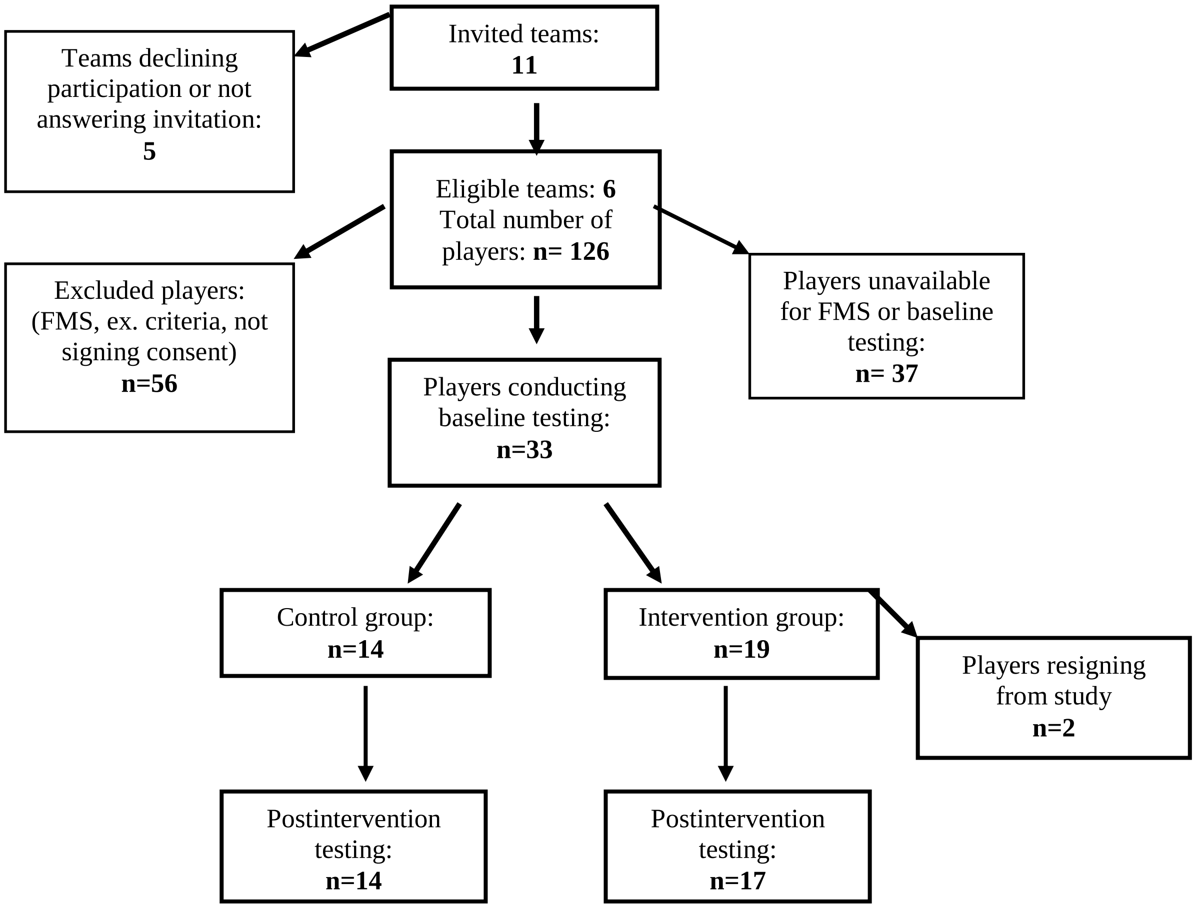

Figure 1. Flow chart of included and excluded players and teams.

Players were excluded from the study if they previously had suffered an ACL injury, if they were flat-footed as described by Lee et al.[76], if they had suffered a serious injury to the back, hip or knee during the previous six months, if they were participating in any organized lower-limb injury prevention training, and if they were below 18 years of age. Prior to inclusion to the study, players were screened for hip and knee control by an experienced physiotherapist using an adapted version of the Functional Movement Screen™ (FMS™)[77,78].

Table 1. Characteristics of study participants. Values are mean±SD unless otherwise stated.

	Intervention group (n=17)	Control group (n=14)	*p*
Age, years	21.7±1.8	20.4±2.7	0.12[b]
Height, cm	170.2±4.8	172.9±5.2	0.15 [b]
Weight, kg	73.6±8.8	69.0±7.1	0.12 [b]
FMS score	6.5±1.2	6.6±0.7	0.75 [b]
Level (n)[a]			<0.01[c]
No. of players ≥ 3. level	9	14	
No. of players ≤ 4. level	8	0	

[a] level of play in Norwegian female handball; [b] Independent samples t-test; [c] Chi square Fischer´s Exact test

The FMS™ is a screening method that uses whole-body, dynamic movements in an attempt to assess the individual´s control of fundamental movement patterns[78]. The goal is to detect if the athlete has any deficiencies in mobility, flexibility and stability. The FMS™ consists of seven movements, with three of these (the deep squat, the hurdle step and the in-line lunge) being used mainly to assess the stability, mobility and flexibility of the hip, knees and ankles[77,78]. In the present study, the adapted version of the FMS™ consisted of 1) the deep squat, 2) the in-line lunge and 3) the hurdle step, with 4) the one-legged squat added to the screening. The latter movement is used in clinical assessments of hip, knee and ankle sensorimotor control[79,80]. The scores obtained in the screening ranged from 0 (lowest) to 3 in each test, and a separate score was given for each leg in all movements. The lowest score for each test was registered and used in the total composite score[77,78]. Scoring criteria for the screening is shown in Table 2. A score of 8 or lower of the composite score of 12 was assumed to indicate reduced knee control[81]. Scoring higher than 8 in the screening resulted in exclusion from the study. The movement screening was also performed at post-test.

2.2 Study design

The study was designed as a controlled trial. Players were assigned to either the control or the intervention group according to the following criteria; 1) players on the same team were placed in the same group in order to avoid players in the control group acquiring information about the intervention training; 2) players on teams located more than 30 minutes drive from the city centre were placed in the control group, in order for each intervention training session to be monitored without substantial travel time and cost; and 3) when four or fewer players were included from a team, these players were placed in the control group.

The physiotherapist conducting the FMS™ at inclusion and post-testing was blinded to which players were placed in the intervention and control group. Examiners conducting the hip abductor strength and jump tests were not blinded, as they also supervised the players during the training intervention. When players were performing the jump tests, they did not receive information on what variables were to be analysed in the study. When conducting all hip abductor strength tests, the responsible examiner did not view the strength values players had obtained on previous strength measurements, but were fully aware of which group the players belonged in.

Table 2. Scoring criteria for the screening procedure in the present study.

Score	Deep squat[78]	In-line lunge[78]	Hurdle step[78]	One-legged squat[80]
3 points	- Upper torso parallel with tibia or toward vertical - Femur below horizontal - Hips aligned over knees and ankles - Dowel aligned over feet - Heels do not require to be elevated	- Dowel remains vertical and in contact with the spine - No movement in torso - Dowel and feet parallel in sagittal plane - Contact between knee and board behind the heel of the front foot	- Hips, knees and aligned in the sagittal plane - Minimal movement in lumbar spine - Dowel and hurdle is parallel	- Hip, knee and foot in line - Pelvis remain horizontally aligned - Upper body vertically aligned
2 points	- 2x6cm board under heels - Upper torso parallel with tibia or toward vertical - Femur below horizontal - Hips aligned over knees and ankles - Dowel aligned over feet	- Dowel does not remain vertical - Movement in torso - Dowel and feet not parallel in sagittal plane - No contact between knee and board behind front foot heel	- Hips, knees and ankles not in line - Movement in lumbar spine - Dowel and hurdle is not parallel	- Hip, knee and foot in line - Pelvis not horizontally aligned - Upper body is not vertical
1 point	- 2x6cm board under heels - Tibia and upper torso is not parallel - Femur not below horizontal - Hips, knees and ankles not in line - Lumbar flexion - Feet not parallel	- Loss of balance	- Contact between foot and string - Loss of balance	- Hip, knee and foot is not in line
0 points	- Subject reports pain during execution	- Subject reports pain during execution	- Subject reports pain during execution	- Subject reports pain during execution

2.3 Data collection

All pre- and post-tests were conducted on the same day for each subject. Height was measured to the nearest ½ cm using a portable SECA 225 height measurer (SECA, Germany). Baseline and post-test weight was measured to the nearest 0.1 kg using a Electronic Scale-9522WB weight (Weighing Apparatus Company Ltd., China). All equipment in need of calibration was calibrated before each new test day or after having been used in other tests the same day.

2.3.1 Hip abductor strength

Isometric hip abductor force output was measured using a handheld dynamometer (Lafayette Manual Muscle Testing System; Lafayette Instrument Company, Lafayette, IN) by the same examiner in all tests. The handheld dynamometer is assumed to be a reliable instrument for strength testing[82], also when measuring hip abductor strength[83]. Hip abductor strength was defined as force output, measured in kilograms (kg), multiplied with an approximation of the length of the anatomical femoral axis[84]. The length of the femur was defined as the distance in metres between the ipsilateral reflexive markers on the femoral greater trochanter and the lateral femoral condyle (see section 2.3.2 below). Strength values were normalized to body weight (force output/ body mass (kg)). Force output measured with the handheld dynamometer does not yield Newton values, but normalized hip abductor strength values are reported as Nm/kg.

All subjects performed a standardized warm-up consisting of two exercises before strength testing; 1x10 bilateral standing hip flexion combined with hip abduction; and 1x10 bilateral standing full range of motion hip abduction. For all strength tests subjects lay on their side with their back against a wall, as the side-lying position is argued to be the most reliable testing position for the hip abductors[85]. All players were tested bilaterally with knees and hips in 180 and 90 degrees, respectively, resulting in four separate strength tests.

In the strength tests, the handheld dynamometer was placed on the lateral femoral condyle, and the player´s pelvis was supported against the wall by the responsible examiner (see Figure 2). The players were instructed to abduct their hip exerting maximal effort against the static resistance applied by the handheld dynamometer and were verbally encouraged by the examiner. All tests were performed with the hip abducted approximately 20 degrees. Subjects were given two submaximal practice trials before performing three maximal voluntary contractions (MVCs) exerting maximal force for three seconds. A rest period of 45-60 sec between each MVC was given to limit the effects of fatigue. To further reduce the effects of fatigue, one side was not tested in both angles consecutively. If the highest MVC measurement was obtained on the third trial, the test was continued until no further strength increase was noted. The peak value of the three (or more) trials in each testing condition was regarded as the subject's MVC, and used in the analysis. Strength test order was counterbalanced between subjects and groups in order to reduce the amount of systematic error introduced by testing order.

Figure 2. Hip abductor strength testing. Left) Knee and hip angle 180 degrees; right) Knee and hip angle 90 degrees.

In addition to pre- and post-intervention hip abductor strength testing, subjects in the intervention group were tested after three and six weeks of the eight-week intervention period. Subjects in the control group were tested 4-5 weeks after baseline testing in addition to pre- and post-testing.

A reliability study was conducted before baseline testing in order to assess the repeatability of the hip abductor strength measurements. Six volunteers met at two separate testing days. All tests were conducted using the same setup and procedures as in the intervention study.

2.3.2 Lower-limb dynamics

To assess lower limb dynamics, four jump tests were performed. These were the counter-movement jump (CMJ), two-legged in-jump landing and bilateral one-legged drop landing from a 30 cm box. Lower limb kinematics were recorded by six Oqus cameras (QualiSys, Gothenburg, Sweden) using 15 lightweight reflexive markers (12 mm), placed bilaterally on the medial and lateral tibial malleoli, the medial and lateral femoral condyles, the femoral major trochanter, the anterior superior iliac spine and the acromion (see Figure 3). One marker was placed on the sacrum (S1).


Figure 3. Marker setup for jump test procedure

The motion capture system was calibrated using a standardized 750 mm calibration wand (Qualisys, Gothenburg, Sweden). A sampling frequency of 250 Hz was used in kinematic recordings. Ground reaction force and centre of pressure was recorded by two Kistler force plates (type 9286BA) (Kistler Instrument Corp., Amherst, NY) using a sample frequency of 500 Hz. In all two-legged tests, subjects landed with one leg on each force plate. For the one-legged tests, subjects landed on one force plate.

In the CMJ test, players were instructed to jump vertically as high as they could, jumping and landing with one leg on each force plate. The in-jump landing required the players to jump horizontally from a 1-metre distance and land with one leg on each force plate. In the one-legged drop-landing test, players stood on a 30 cm high box, and dropped down to land on one force plate. See Figure 4 for pictures of the jump tests. Players were in all tests required to maintain their balance after landing for a successful trial to be approved. In all tests, the players held their hands on their waist to minimize masking of reflexive markers. Each player was given two or more practice trials before each test, to minimize learning effect differences between players and groups and between pre- and post-test results. Three consecutive trials on each jump-landing test were then recorded and used in the analysis.

For the one-legged landings in the pre-tests, the average of the two last trials was used in the data analysis. All three trials were not used in the analysis because some players were given too few practice trials, resulting in a markedly different landing technique in the first trial of these cases.

Figure 4. Jump tests in the present study. Left) CMJ; middle) in-jump; right) one-legged landing (also performed on the left leg (not shown)).

2.4 Intervention training program

The hip abductor strength and sensorimotor control training program was conducted 2d/w for eight weeks. Each session was held immediately after the team training of the teams in the intervention group. The exercises were performed with three sets of 8-12 repetitions. The exercises were 1) side-lying hip abduction, 2) Bulgarian squat with medially directed resistance, 3) supine hip abduction with bilateral medially directed resistance and 4) horizontal jumps with bilateral medially directed resistance (see Figure 3). Each exercise was individually progressed, with subjects starting at eight repetitions on the lowest intensity level, and then progressing through 10 to 12 repetitions on the same intensity level. When 12 repetitions at one intensity level were performed successfully, subjects again started on eight repetitions at a higher intensity level. Each intervention training session was monitored by one or both of the responsible researchers in order for exercises to be carried out with correct technique and movement speed, as will be described in the following.

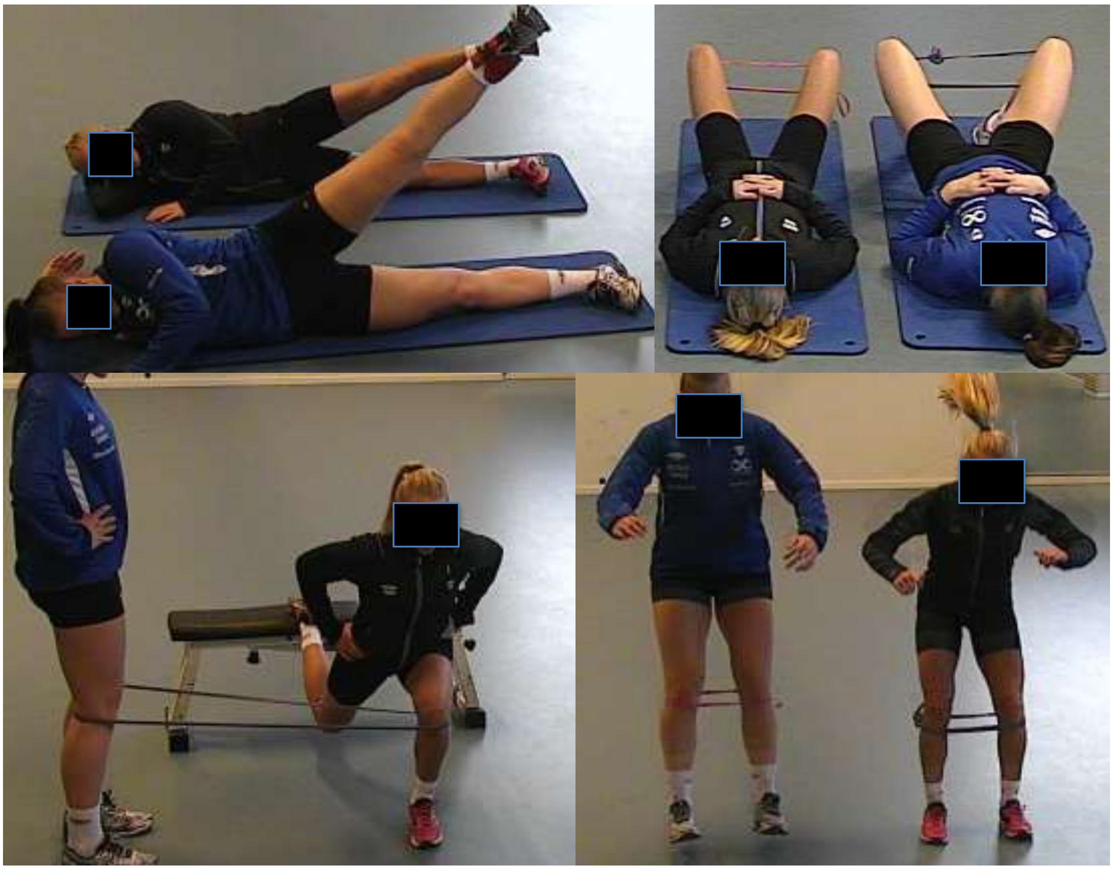

Figure 5. Intervention training program exercises. Top left) Side-lying hip abduction; bottom left) Bulgarian squat with medially directed resistance; top right) Supine hip abduction with medially directed resistance; and bottom right) Horizontal jumps with medially directed resistance.

In 1) the side-lying hip abduction, the players abducted the top leg away from the midline of the body and were required to maintain straight hip and knee joint angles. Weights (1kg) were added around the ankle when players were able to perform 3x12 unloaded repetitions with proper movement speed without difficulty. In 2) the Bulgarian squat, elastic bands (Kappi, Norway) added a medially directed resistance. An elastic band was placed around the proximal end of the tibia, just below the patella, demanding recruitment of the hip abductors to maintain the hip, knee and ankle in neutral medio-lateral alignment. In 3) the supine hip abduction, the hip flexion angle was approximately 60 degrees, and the sole of the feet were in contact with the floor. An elastic band was placed around the knee joints just below the patella, and players abducted their hip as far as they could, with the lower back in contact with the floor. The concentric phase counted 2 seconds and the eccentric phase counted 3 seconds. In 4) the horizontal jumps, an elastic band was placed around the legs just below the patella when subjects stood with feet together. The players were required to perform the jumps with feet shoulder-width apart. Players jumped horizontally, and the movement speed and force of the jumps were individually progressed. Proper technique was defined as having the hip, knee and ankle in line with each other in both take-off and landing, demanding recruitment of the hip abductors. When players performed successful jump-landings with slow movement speed, the resistance of the elastic bands and the force and speed of the jumps were increased.

The duration of the training session was designed to not exceed 15 minutes. The training was performed immediately after the team training to increase the probability of players attending the session, as well as potentially reduce the non-contact ACL injury risk compared to conducting the training prior to the team training session[70]. At every training session, at least one of the two responsible researchers was present in order to monitor individual progression and ensure that exercises were performed with proper technique and movement speed.

2.5 Data analysis and statistics

Reflexive marker trajectories in the jump tests were tracked and calculated by Qualisys Track Manager (Qualisys, Gothenburg, Sweden). To calculate lower limb dynamics, a customized Matlab script (MathWorks, Inc, Natick, Massachusetts) was designed. Data was resampled to the same frame rate of 250 Hz for kinetic and kinematic data and low-passed filtered at 15Hz using an 8th order recursive Butterworth filter. Knee abduction moment was calculated for a time window of 200 msec before take-off in the CMJ test and 300 msec after initial contact of landing in all tests for both legs. Maximal knee abduction moment, maximal knee valgus angle and knee valgus and flexion angle at the time of maximal knee abduction moment were identified in the same time periods for both legs. Jump height was defined as sacrum marker displacement.

In the customized Matlab script, a local coordinate system was defined. Origo of the local coordinate system was defined as the midpoint between the two ankle markers. The shank was defined as the segment between the midpoint of the ankle and knee markers. All marker and force data was rotated in all three planes. This rotation defined the shank in a vertical position in the sagittal and frontal plane and with no rotation in the horizontal plane, and also defined the midpoint of the knee to be directly above the midpoint of the ankle. Take-off and landing phases were, respectively, defined as the point in time when force became lower than or exceeded 10 N as recorded by the force plates.

Knee abduction moment was defined as the product of the ground reaction force multiplied with the frontal plane distance between the midpoint of the knee and the orientation of the ground reaction force vector. The orientation of the ground reaction force vector was determined based on the centre of pressure recorded by the force plates. Knee abduction moments are reported as values normalized to body mass (Nm/body mass (kg)) unless otherwise stated. Positive values indicate a knee abduction moment, and negative values indicate a knee adduction moment, i.e., a knee in varus.

Knee valgus angle was defined as the frontal plane angle between the lateral knee marker and the ipsilateral femoral trochanter marker. Positive values indicate valgus. Knee flexion angle was defined as the sagittal plane angle between the lateral knee marker and the ipsilateral femoral trochanter marker. Positive values indicate flexion. When ankle markers were masked, the local coordinate system origo was not possible to define, and some players therefore do not have data in all jump tests.

Statistical analyses were performed using SPSS version 21 (SPSS, IBM Corporation). To investigate if compliance influenced hip abductor strength change, three compliance categories were defined: Category 1 (percentage compliance <74.99 %), category 2 (75 % - 89.99 %), and category 3 (>90 %). To investigate if hip abductor strength increase was associated with reductions in knee abduction moment and knee valgus angle, players in the intervention group increasing their normalized hip abductor strength above 0.001 Nm/kg from baseline to post-test were compared to those in the intervention group not increasing in strength, as defined by a strength change of 0.00 Nm/kg or lower.

The intra-tester reliability of the handheld dynamometer measurements was assessed using intraclass correlation coefficients (ICC). Differences between groups at baseline were analysed using independent samples t-tests for continuous variables, and a Chi square test was used for categorical variables. To compare strength change between compliance categories and jump height change between intervention and control group, and to compare changes in knee abduction moment and knee valgus angle between strength categories in the intervention group and between the intervention and the control group, mixed design repeated measures analysis of variance (ANOVA) were performed. Effect sizes are reported as partial eta squared values.

Data was controlled for normality using Q-Q-plots and assessed using the Shapiro-Wilk’s test. Cases were excluded listwise. Most kinetic and kinematic variables were normally distributed (62 out of 68 variables). Homogeneity of variance was tested using Levene’s test. Most kinematic and kinetic variables did not violate the assumption of homoscedasticity (65 out of 68 variables). All hip abductor strength values were normally distributed and variance was homogeneous at both pre- and post-test.

3.0 Results

3.1 Hip abductor strength reliability study

Table 3 shows the ICC for the repeated hip abductor strength tests performed prior to study start (pilot study). The results indicate very good to excellent test-retest reliability of the hip abductor strength tests both with extended hip/knee joints (180 degrees) and flexed hip/knee joints (90 degrees).

Table 3. Test-retest reliability of pilot study hip abductor strength tests.

Test leg and knee and hip angle	Intraclass Correlation Coefficient (95 % Confidence Interval)
Right leg 180 degrees	0.99 (0.94, 1.00)
Right leg 90 degrees	0.85 (0.27, 0.98)
Left leg 180 degrees	0.98 (0.88, 1.00)
Left leg 90 degrees	0.95 (0.68, 0.99)

3.2 Subject characteristics

Table 1 shows characteristics of participating subjects. No significant differences were found in subject characteristics between intervention and control group at baseline. Weight was reduced significantly in both groups combined from pre- to post-test ($F_{(1,29)}=6.46$, $p=0.17$, effect size(ES)=0.18), but no between-groups differences in weight change was evident ($F_{(1,29)}=0.7$, $p=0.4$, ES=0.02). There were significantly more players at the third level or higher in the control group compared to the intervention group ($p<0.01$).

3.3 Hip abductor strength

Table 4 presents the normalized hip abductor strength values for the intervention group and control group at baseline, mid-protocol and post-test for all four strength tests. Hip abductor strength did not change significantly in the intervention group compared to the control group from baseline to post-test in any test ($p>0.05$), and effect sizes were small.

Compliance to the training intervention ranged from 25% to 100% with an average compliance of 73.2%. The average compliance corresponded to missing four to five out of the total 18 exercise sessions. No significant effect of compliance to the training program on hip abductor strength change was found. A tendency towards significant effect of above 90% compliance (n=4) compared to lower compliance (n=13) on normalized hip abductor strength increase was found in the 180 degrees hip abductor strength test in the left ($F_{(1,15)}=3.8$, $p=0.07$, ES=0.20) and the right leg ($F_{(1,15)}=3.7$, $p=0.07$, ES=0.20), and in the 90 degrees hip abductor strength test in the left leg ($\mathrm{F}_{(1,15)}=4{,}5$, $p=0.052$, ES=0.23) but not the right ($\mathrm{F}_{(1,15)}=0.004$, $p=0.95$, ES=0.00).

Table 4. Normalized hip abductor strength values at baseline, mid-protocol and post-test for intervention (INT) and control (CON) group.

		Hip abductor strength (Nm/kg)[a] (mean±SD)					
Test[b]	Group	Pre-test	Mid-protocol[c]		Post-test	Effect size[d]	*p*
Left 180	INT	0.17±0.04	0.16±0.03	0.15±0.03	0.16±0.03	0.05	0.23
	CON	0.17±0.03	0.17±0.03		0.15±0.02		
Right 180	INT	0.17±0.04	0.17±0.04	0.16±0.04	0.16±0.03	0.00	0.95
	CON	0.16±0.04	0.16±0.03		0.15±0.02		
Left 90	INT	0.14±0.03	0.15±0.03	0.14±0.03	0.14±0.03	0.004	0.73
	CON	0.14±0.03	0.14±0.03		0.14±0.03		
Right 90	INT	0.14±0.03	0.15±0.03	0.15±0.02	0.15±0.02	0.06	0.18
	CON	0.13±0.03	0.13±0.03		0.13±0.02		

[a] Normalized to body mass; [b] Leg (left, right) and hip and knee angle (180 degrees, 90 degrees); [c] Intervention group was tested at 3 (n=17) and 6 weeks (n=14) during the intervention training period, control group was tested 4-5 weeks after pre-test; [d] Effect size for change from pre- to post test in intervention group compared to control group.

3.4 Knee abduction moment

Table 5 shows normalized knee abduction moments in both groups at pre- and post-test in all jump-landing tests. Figure 6 shows the mean (±SD) non-normalized knee abduction moment in the intervention group for both legs at pre- and post-test in the take-off (A and B) and landing (C and D) of the CMJ test. Knee abduction moment was significantly different between groups at baseline in the right leg in the one-legged landing (t=2.8, p=0.01). Knee abduction moment was significantly reduced in the intervention group compared to the control group in the take-off of the CMJ test in the right ($F_{(1,21)}$=4.9, p=0.041, ES=0.22) and left leg ($F_{(1,21)}$=4.4, p=0.05, ES=0.20). In the landing of the CMJ test, a tendency towards significant reduction compared to the control group was found in the right leg ($F_{(1,18)}$=3.4, p=0.085, ES=0.17) but not the left ($F_{(1,18)}$=0.2, p=0.67, ES=0.01). In all other tests, the intervention group did not change significantly compared to the control group.

In the intervention group, players that increased in strength in the 180 degrees hip abductor strength test (leg, number of players, mean strength increase; right, n=5, 0.24 Nm/kg; left, n=6, 0.20 Nm/kg) did not significantly reduce their knee abduction moment compared to those who did not increase in strength in any test (data not shown).

3.5 Knee angles

Table 6 show maximal knee valgus angles at baseline and post-test for intervention and control group in all jump-landing tests. Maximal knee valgus angle was significantly different between groups at baseline in the in-jump test in the left (t=3.3, p=0.003) and right leg (t=2.3, p=0.03) and in the one-legged landing test in the right leg (t=3.8, p=0.001). Maximal knee valgus angles did not change significantly in the intervention group compared to the control group in any test. A 44% absolute reduction in maximal knee valgus angle in the left leg in the in-jump test in the intervention group did not reach statistical significance when compared to the control group ($F(_{1,15})$=3.8, p=0.07, ES=0.2).

Table 5. Normalized knee abduction moments (Nm/kg) in intervention (INT) and control (CON) group at baseline and post-test

				Knee abduction moment [a] (mean±SD)			
Test	Measure	Group	n	Pre	Post	Effect size	*p*
CMJ	Take-off left	INT	13	0.82±0.34	0.66±0.40	0.24*	**0.05**
		CON	10	0.68±0.16	0.69±0.16		
	Take-off right	INT	12	1.05±0.40	0.90±0.41	0.22*	**0.04**
		CON	10	0.89±0.40	0.97±0.31		
	Land left	INT	13	1.63±0.69	1.37±0.55	0.01	0.70
		CON	11	1.85±0.96	1.45±0.80		
	Land right	INT	12	2.26±1.00	1.96±0.75	0.17	0.09
		CON	10	2.31±1.18	2.31±1.11		
In-jump	Land left	INT	14	0.29±0.22	0.23±0.16	0.01	0.60
		CON	12	0.48±0.48	0.39±0.32		
	Land right	INT	11	0.69±0.40	0.75±0.50	0.00	0.96
		CON	10	0.70±0.58	0.68±0.62		
One-leg	Land left	INT	13	-0.13±0.09	-0.06±0.08	0.01	0.70
		CON	11	-0.14±0.13	-0.11±0.08		
	Land right	INT	13	0.19±0.18[Δ]	0.19±0.19	0.04	0.40
		CON	10	-0.09±0.28	0.09±0.28		

[a] adjusted for hip abductor strength at baseline, and hip abductor strength change and jump height change (CMJ only) from baseline to post-test; *significant change from pre- to post-test compared with control group ($p<0.05$); [Δ] significantly different from control group at baseline ($p<0.05$).

Table 7 shows change in knee valgus angle at the time of maximal knee abduction moment from baseline to post-test. Knee valgus angle at the time of maximal knee abduction moment was significantly higher in the intervention group compared to the control group in the landing of the CMJ test in the right ($t=2.8$, $p=0.01$) and the left leg ($t=2.5$, $p=0.02$), in the in-jump test in the right ($t=3.2$, $p=0.01$) and the left leg ($t=4.4$, $p<0.001$), and in the one-legged landing test in the right leg ($t=2.9$, $p=0.01$). Mean knee valgus angle at the time of maximal knee abduction moment was significantly reduced in the intervention group compared to the control group in the left leg in the in-jump test ($F_{(1,15)}=10.3$, $p=0.006$, ES=0.35) and tended towards significant reduction in the right leg in the in-jump test ($F_{(1,15)}=3.1$, $p=0.098$, ES=0.17) and the right leg in the take-off of the CMJ ($\mathrm{F}_{(1,17)}=4.3$, $p=0.054$, ES=0.20).

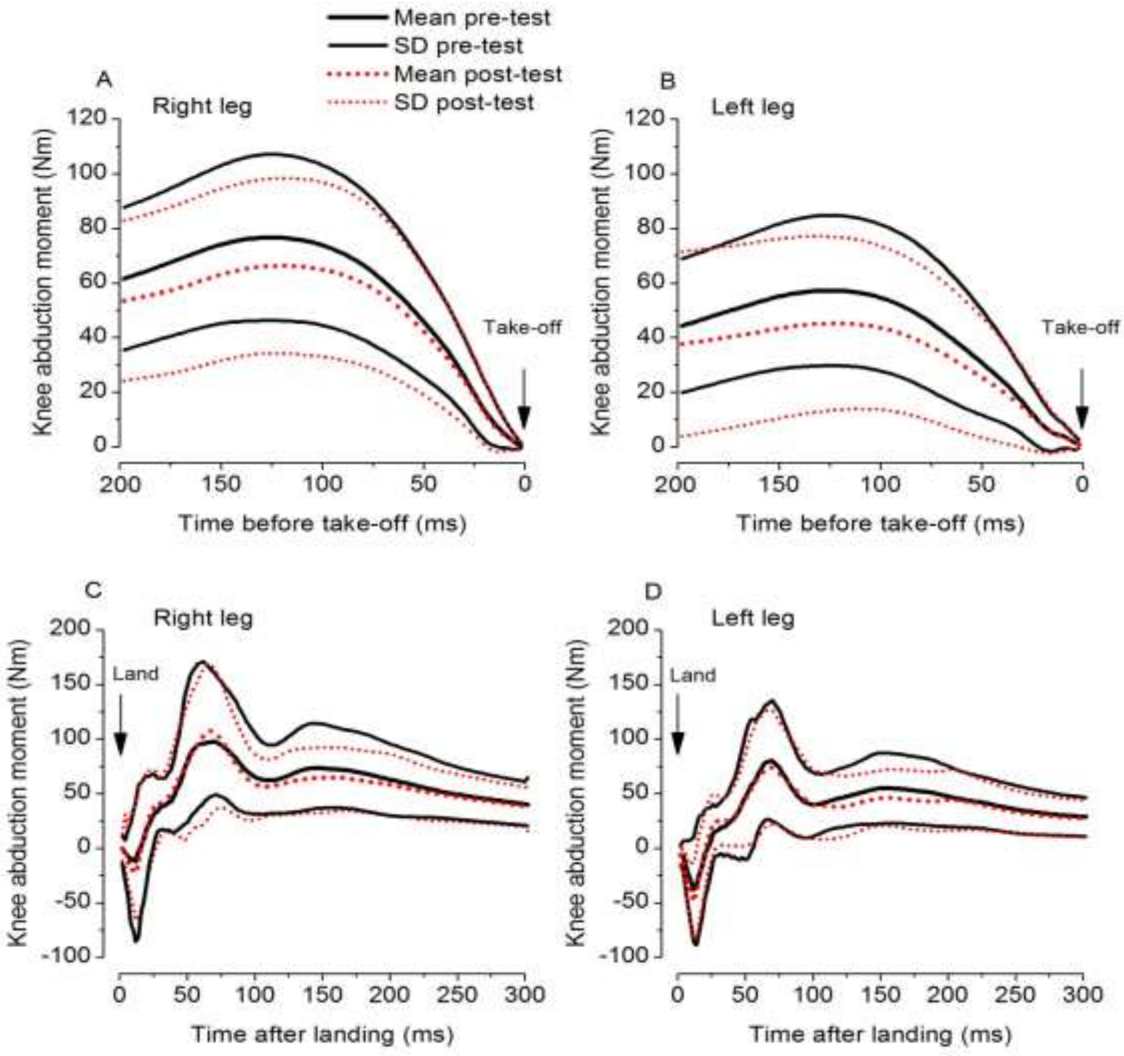

Figure 6. Mean (±SD) knee abduction moment 200 msec before take-off (A and B) and 300 msec after landing (C and D) in the CMJ test in intervention group at the pre- (solid) and post-test (dotted). Positive values indicate knee abduction moment (valgus) and negative values indicate knee adduction moment (varus).

Maximal knee valgus angle in players increasing in hip abductor strength compared to players not increasing in strength in the intervention group increased significantly in the one-legged landing in the right leg ($F_{(1,10)}$=7.76, p=0.034, ES=0.40) but not the left ($F_{(1,11)}$=1.07, p=0.32, ES=0.09) and in the landing of the CMJ test in the right leg ($F_{(1,9)}$=6.23, p=0.034, ES=0.41) but not the left ($F_{(1,10)}$=1.09, p=0.32, ES=0.10). Similar trends were also found for knee valgus angle at the time of maximal knee abduction moment (data not shown).

The intervention group had significantly lower knee flexion angle at the time of maximal knee abduction moment at baseline compared to the control group in the left leg in the in-jump test (*t*=-2.5, *p*=0.001). Knee flexion angle at the time of maximal knee abduction moment did not change significantly from baseline to post-test in the intervention group compared to the control group in any test. A tendency towards significantly reduced knee flexion angle at the time of maximal knee abduction moment from pre- to post-test was found in the control group compared to the intervention group in the left leg in the in-jump test ($F_{(1,17)}$=3.7, *p*=0.07, ES=0.18).

Table 6. Maximal knee valgus angle in intervention (INT) and control (CON) group at pre- and post-test

				Maximal knee valgus angle[a] (mean±SD)			
Test	Measure	Group	n	Pre	Post	Effect size	*p*
CMJ	Take-off left	INT	13	25.2±6.3	22.6±8.5	0.005	0.80
		CON	10	21.0±6.9	18.9±4.4		
	Take-off right	INT	12	28.6±9.5	25.4±8.0	0.02	0.30
		CON	10	21.0±9.7	24.3±7.2		
	Land left	INT	13	24.4±5.8	23.2±7.0	0.00	0.90
		CON	10	19.6±6.7	17.6±4.4		
	Land right	INT	12	26.8±8.6	24.6±6.0	0.11	0.18
		CON	10	20.3±8.4	21.0±5.7		
In-jump	Land left	INT	10	23.8±5.8$^{\Delta}$	15.7±8.8	0.20	0.07
		CON	9	12.7±4.5	11.4±3.2		
	Land right	INT	11	25.1±7.7$^{\Delta}$	21.0±8.2	0.06	0.35
		CON	8	18.4±5.5	17.8±8.2		
One-leg	Land left	INT	13	23.2±7.2	21.8±6.7	0.001	0.90
		CON	11	16.8±4.3	15.0±3.8		
	Land right	INT	12	25.3±7.0$^{\Delta}$	25.3±7.9	0.06	0.30
		CON	10	15.4±4.7	17.8±6.0		

[a] adjusted for hip abductor strength at baseline, hip abductor strength change (normalized to body mass) and jump height change (CMJ only) from pre- to post-test; *significant change from pre- to post-test compared with control group at $p<0.05$; $^{\Delta}$ significantly different from control group at baseline ;

3.6 Jump height

Jump height in the CMJ test increased significantly in the control group (n=12; mean change=2.5 cm) compared to the intervention group (n=12; mean change=0 cm) ($F_{(1,22)}$=7.0, *p*=0.015, ES=0.24) from baseline to post-test in those players with jump height data at pre- and post-test.

Table 7. Knee valgus angle at the time of maximal knee abduction moment in the intervention (INT) and control (CON) group at pre- and post-test.

				Knee valgus angle [a] (mean±SD)			
Test	Measure	Group	n	Pre	Post	Effect size	*p*
CMJ	Take-off left	INT	13	25.2±6.3	21.6±8.6	0.01	0.65
		CON	10	20.3±7.9	17.4±5.3		
	Take-off right	INT	12	28.0±9.6	24.8±8.1	0.20	**0.05**
		CON	10	19.5±9.1	21.6±8.4		
	Land left	INT	13	19.2±4.8 [Δ]	18.5±5.3	0.001	0.90
		CON	10	12.7±5.3	11.6±3.7		
	Land right	INT	12	19.7±7.4 [Δ]	19.0±4.1	0.03	0.52
		CON	10	12.6±4.2	12.8±3.4		
In-jump	Land left	INT	10	22.0±6.3 [Δ]	16.1±6.9	0.36*	**0.01**
		CON	9	9.0±4.4	9.7±3.7		
	Land right	INT	11	22.3±8.4 [Δ]	18.1±8.5	0.17	0.10
		CON	8	14.5±3.3	15.6±7.1		
One-leg	Land left	INT	13	16.6±7.4	21.8±6.7	0.00	0.94
		CON	11	11.3±3.2	15.0±3.8		
	Land right	INT	12	21.9±7.6 [Δ]	21.6±8.1	0.01	0.69
		CON	10	13.4±4.2	12.7±3.2		

[a] adjusted for hip abductor strength at baseline, hip abductor strength change (normalized to body mass) and jump height change (CMJ only) from pre- to post-test; *significant change from pre- to post-test compared with control group at $p<0.05$; [Δ] significantly different from control group at baseline

4.0 Discussion

The aim of this study was to prospectively assess the relation between hip abductor muscle strength and frontal plane knee joint kinetics and kinematics in female handball players with reduced knee control. In the present study, reductions in knee valgus angle and knee abduction moment were not related to increases in hip abductor strength in players in the intervention group increasing in strength compared to those that did not increase in strength. However, the hip abductor strength and sensorimotor control training program in this study was not sufficient to increase hip abductor strength in the intervention group compared to the control group in any test. Compliance was low, with considerable inter-individual variation, and a tendency towards a significant effect of training on hip abductor strength increase was found in players at or above 90% compliance. Despite no increase in hip abductor strength, the intervention group significantly reduced knee abduction moments compared to the control group in the take-off in the counter-movement jump. Moreover, the intervention group showed a tendency towards significant reductions in knee abduction moment compared to the control group in the landing in the counter-movement jump in the right leg, but not in the left leg. Reductions in knee valgus angle in the intervention group only reached statistical significance in some tests when compared to the control group.

4.1 Hip abductor strength

The intervention group did not increase in hip abductor strength compared to the control group in the present study. The lack of strength improvements could be due to low compliance[61], resulting in a too low resistance training volume to elicit strength gains[86]. The average compliance was 73.2%, and the majority of players in the intervention group had lower than 90% compliance. Additionally, there was a tendency towards a significant increase in hip abductor strength in three out of four tests for players with above 90% compliance. This could indicate that the hip abductor intervention training program could have had an effect on strength increase if all players had compliance at or above 90%.

The intervention training program was conducted immediately after the team training session. Conducting concurrent resistance and endurance training can negatively affect strength gains[87,88], possibly due to counteracting molecular responses elicited by the two different forms of training[87]. This could explain some of the lack of strength increase in the intervention group. Team handball training also likely results in a notable amount of fatigue. Within each intervention training session players could therefore have had a diminished physiological ability to perform exercises with proper technique and effort[89], even when verbally encouraged and monitored by the responsible examiners. During the course of the eight-week in-season intervention training period, players could also have experienced a total training and match volume too high to be able to recover properly in order for strength gains to be elicited. The lack of strength gains could therefore partly be an effect of persistently low glycogen levels and a high protein turnover[87,88].

Several studies have elicited a significant increase in hip abductor strength using similar designs as this study[64,72-74]. These studies have implemented three sessions per week for four to six weeks in recreationally active females. The intervention training in the present study consisted of two 20-minute sessions per week for eight weeks, and implemented resistance training exercises similar to exercises used in some[64,74] but not other studies[72,73] that have increased hip abductor strength. The exercises used were assumed to effectively activate hip abductors such as the gluteus medius[90]. Two out of four exercises in the intervention training program were standard resistance exercises for the hip abductors (the side-lying hip abduction and supine hip abduction), while the remaining two exercises (the Bulgarian squat and jump-landing) focused on recruitment of the hip abductors to resist hip adduction in whole-body movements. Two sessions per week with few hip abductor resistance training exercises coupled with low compliance could have resulted in a too low resistance training volume to elicit strength gains[86].

Additionally, it was not possible to ensure minimum of 48 hours of rest before the hip abductor strength tests both at pre- and post-test. Differences in fatigue levels between test days, groups and players could have introduced some random error to the strength testing procedure. Other potentially biasing factors, such as hip abduction angle differences between tests[91] and examiner strength[92] could have influenced the results. However, the test-retest reliability of the hip abductor strength test procedure in this study was found to be very good to excellent, as also shown in other studies[83,85], which could indicate that these potentially biasing factors did not influence the results substantially.

4.2 Frontal plane knee joint dynamics

The intervention group significantly reduced maximal knee abduction moments compared to the control group in the take-off in the CMJ and tended towards a reduction in the landing in the CMJ. These reductions were not associated with increases in hip abductor strength in those players increasing in strength in the intervention group, which could support other published findings[74]. Studies implementing training interventions with varying focus on plyometric, resistance, balance and technique training have prospectively reduced knee valgus angles and knee abduction moments in males[55,56] and females[93-95]. These studies show that improvements in frontal plane knee control can occur without training interventions focusing on increasing hip abductor strength.

Knee valgus angle at the time of maximal knee abduction moment was reduced by 3-4 degrees in the right and left leg in the take-off in the CMJ in the present study. This could to some extent explain the reduction in maximal knee abduction moment in the intervention group compared to the control group. The reduction in knee valgus angle resulted in approximately 20% reduction in maximal knee abduction moment in both legs in the take-off in the CMJ. This is consistent with other findings, where a reduction of 4.4 degrees knee valgus corresponded to a 19% reduction in knee abduction moment in sidestep cutting[96]. Reducing the knee valgus angle will move the knee centre laterally and closer to the orientation of the ground reaction force vector and thus reduce the knee abduction moment[97].

Two out of four exercises in the intervention training program in the present study focused on recruitment of the hip abductor muscles to resist hip adduction and knee valgus in dynamic, whole-body movements. The recruitment of these muscles in sport-specific movements might be a key factor in preventing potentially injurious knee abduction moments and knee valgus angles[45,64]. The results from the present study could indicate that the reductions in knee valgus angle and knee abduction moment in the take-off in the CMJ was elicited by improvements in the magnitude and timing of hip abductor recruitment during take-off, thus improving the ability to resist hip adduction and reduce knee valgus angles[98]. However, the control group significantly increased in jump height compared to the intervention group in the CMJ test from pre- to post-test. The control group did not increase in knee abduction moment in the CMJ test from pre- to post-test despite the likely increase in generation of ground reaction forces. Some of the improvements in the intervention group relative to the control group could be explained by the increase in jump height in the control group, and this needs to be considered when interpreting the results in the present study.

A reduction of 0.7 degrees knee valgus in the landing of the CMJ in the present study resulted in approximately 20% decrease in maximal knee abduction moment in the intervention group, although this reduction tended towards statistical significance only in the right leg and not the left when compared to the control group. The reason for reductions in maximal knee abduction moments in the landing of the CMJ without concurrent reductions in knee valgus angle could be explained by a more muscle-dependent absorption of ground reaction forces, for example by increasing the reliance on fore-foot landing[26,28]. In the landing in the CMJ test the ground reaction forces generated were of greater magnitude and they were generated more rapidly compared to the take-off. There was therefore likely a demand for greater and more rapid recruitment of the hip abductors in order to resist hip adduction in the landing compared to the take-off phase.

Also in the one-legged landing, knee valgus angles were not reduced in the intervention group compared to the control group, and small absolute changes were evident. The one-legged landing test is similar to the injury situation for the majority of non-contact ACL injuries[21-24], while the landing of the CMJ test elicited the largest knee abduction moments in the present study, and thus potentially the highest injury risk[62]. The intervention group therefore did not reduce knee valgus angles or knee abduction moments compared to the control group in those conditions eliciting the theoretically highest risk of injury in the present study. This could indicate that to improve frontal plane knee control in situations that theoretically elicit the highest risk for suffering a non-contact ACL injury, higher training loads than in the present study is necessary for significant improvements.

Additionally, sub-analyses showed that players in the intervention group increasing in hip abductor strength from pre- to post-test tended towards an increase in knee valgus angles in some test conditions compared to players not increasing in hip abductor strength. Few subjects increased in strength and these trends should be interpreted with caution and not emphasized strongly. However, stronger hip external rotators have previously been correlated with increased frontal plane knee joint displacement[99] and some suggest that high hip abductor activation might not be beneficial in sidestep cutting[100]. Several other factors such as postural control of the trunk[97,101] and arm position[102] could also affect frontal plane knee loading. The performance of the hip abductors is therefore not the only factor influencing frontal plane knee loading and should likely be a consideration when designing non-contact ACL injury prevention programs.

4.3 Practical implications

Intervention training studies prospectively improving frontal plane knee control in jump tasks in females[93-95] have implemented sessions of either 90 minutes two to three times per week[95] or a shorter duration with a frequency of four to six days per week[93,94]. The total training load in the present study could therefore generally be too low to improve not only hip abductor strength but also frontal plane knee control in those situations mimicking the non-contact ACL injury situation or evoking the largest challenges to frontal plane knee control, such as landings. This could present a major challenge for non-contact ACL injury prevention. Studies implementing 90-minute sessions two to three times per week are likely very difficult to apply to the real world sport setting. Team sport coaches will likely not dedicate this amount of time to injury prevention training, as it will be perceived to take time away from improving sport performance. This could in turn lead to no injury prevention training being performed at all, further affecting injury risk.

As also shorter duration prevention training programs with higher frequency can reduce non-contact ACL injury risk factors, they are a promising alternative in non-contact ACL injury prevention. These training programs could be incorporated into the team training or warm-up and focus on both reducing injury risk and improving performance variables such as jump height, sprint speed and strength. This could improve compliance[60], further improving the effects of the prevention training[61]. Improving performance variables with such injury prevention training programs is also possible[103]. Especially in females, incorporating injury prevention training programs in early adolescence might be a key factor in reducing the spike in injury incidence occurring around 15-19 years of age[32], by counteracting the assumed neuromuscular deficits occurring during the growth spurt in this period[104].

In the present study, all jump tests elicited similar knee valgus angles, which is contradictory to some findings[105], and dissimilar knee abduction moments. Most notably, smaller knee abduction moments were generated in the one-legged landings compared to the other tests. In some of the one-legged landings, knee adduction moments were elicited, originating from a ground reaction force vector orientation passing just medial to the defined knee joint centre. Knee joint dynamics have been found to be significantly different between drop jumps and sidestep cutting tasks[106] and improvements in knee kinetics have been shown to be inconsistent between testing conditions[93] in females. Assessing knee joint dynamics in two-legged jumping tasks might therefore not correlate with the dynamics in movements that resemble the non-contact ACL injury situation, such as one-legged landings or sidestep cuts[106], and should be a consideration when screening for non-contact ACL injury risk. Additionally, a one-legged drop or stop jump might have elicited more sport-specific movement characteristics, and should likely have been incorporated in the present study.

4.4 Non-contact ACL injury prevention

In the present study, all jump tests were performed with athletes given enough time to plan the movement. Anticipated movements elicit different lower-limb dynamics compared to unanticipated movements[107] and fatigue can increase lower-limb risk factors for non-contact ACL injury[70,71,108,109]. The combined effects of fatigue and decision-making could further increase these risk factors[110]. Caution should therefore be made when using the results from studies such as the present one to imply anything regarding alterations to knee valgus angles and knee abduction moments in sport settings where fatigue and anticipation and planning of movements will influence the lower-limb dynamics.

The non-contact ACL injury likely results from forces acting on the ACL in all three planes[26,28], where especially in females poor knee control in the frontal plane is proposed as a common injury risk factor[62,63]. The hip abductors therefore likely play a role in non-contact ACL injury prevention, but the results from the present study cannot support that solely focusing on resistance training of the hip abductors can improve frontal plane knee control.

Resistance training has been found to be a key component in non-contact ACL injury prevention programs[59]. It is however likely needed in combination with other exercise modalities, especially plyometric and postural control exercises to be effective in reducing the incidence of non-contact ACL injuries[59,60]. Stearns et al.[73] found an association between increased hip abductor strength and improved frontal plane knee control in a jump task, whereas Herman et al.[74] did not. The reason for this discrepancy could be due to the fact that Stearns et al. implemented a multicomponent training program[75], whereas Herman et al. focused solely on resistance training[74]. This could further support the notion that resistance training alone is not sufficient to improve frontal plane risk factors for non-contact ACL injuries[59,60,74].

Injury prevention studies have shown promising results in reducing non-contact ACL injury incidence[51,53,111,112]. To further improve the promising results, future injury prevention programs likely need to begin in early adolescence[104] and be designed as multicomponent training programs[59]. The training should be incorporated into the team training and also focus on performance enhancements[60,61], which could improve compliance[61]. Incorporating exercises that challenge postural and segmental control in all three planes, including muscles both distal and proximal to the knee[101,102,113], and implementing sport-specific technique training[114] with some level of fatigue[110] could also prove beneficial.

For non-contact ACL injury prevention, the number of players that need to perform injury prevention training to avoid a single injury has been proposed to be as high as 108 players[115]. Development of effective screening methods to identify players at high risk of suffering a non-contact ACL injury and targeting these players specifically could be one way to reduce the numbers needed to treat as well as the incidence of injury[78,115]. Such screening procedures might even need to incorporate some assessment of neurocognitive function, as non-contact ACL injured athletes have been reported to have significantly lower reaction time and processing speed on cognitive tasks compared to uninjured controls[116]. Detailed and comprehensive screening and follow-up could also enable development of individualized injury prevention training programs that would likely be more effective in reducing the risk of the debilitating non-contact ACL injury.

4.5 Strengths and limitations

This study was designed as a prospective controlled study rather than a randomized controlled trial (RCT), as a RCT would likely lead to players on the same team ending up in both the control and intervention group. This could potentially have affected the results, as players in the control group could have done similar exercises as the intervention group, altering their hip abductor strength and knee control more than would be expected. The responsible examiners were present at every training session conducted by the three teams in the intervention group to ensure that exercises were performed with proper technique. This does however not ensure that players were motivated and performed the exercises with the desired effort, despite being verbally encouraged throughout the session.

The kinetic and kinematic data were collected in a standardized procedure, and should have limited sources of error. The kinetic and kinematic data derived from the first of three one-legged landings at pre-test were not used in the analysis. The landing pattern in some players in the first one-legged landing was markedly different compared to the second and third, and including these data could have led to the results being biased by a difference in rehearsal trials from pre- to post-test. The present study could have conducted the hip abductor intervention training within each team training session, and thus likely improved compliance. This could however have led to fatigue of the hip abductors which in turn could have increased risk factors for suffering a non-contact ACL injury within the team training[70], especially when combined with fatigue of other muscles[108,117]. The decision was therefore made to perform the intervention training after the team training session

The lack of effect on hip abductor strength increase is clearly a limitation that should be considered when interpreting the results. The total training load could have been too high and the volume of hip abductor resistance training too low to elicit strength gains in the intervention group. A pilot study investigating the potential effects of the training program in the present study should have been conducted prior to study start. The training program in the present study could also have included a larger amount of specific hip abductor resistance exercises compared to exercises focusing on recruitment of the hip abductors in whole-body movements, and added a third intervention training session per week to increase resistance training volume. Additionally, reflexive markers were masked in several trials in the jump tests, which reduced the number of players yielding data to the analysis, thus reducing the statistical power of the present study. A static standing calibration of each player should have been performed before conducting the tests to avoid this problem. Large absolute reductions in knee valgus angle in the intervention group in some tests did not reduce the knee valgus angle to the level of the control group, and could indicate some differences were present between groups at baseline.

Differences in marker placement from pre- to post-test and marker movement artefacts could have influenced the results, but measures were taken to reduce these potential sources of bias. Differences in fatigue level between and within players, test days and groups could have influenced the results both from the strength and jump tests. Players in both groups could also have experienced a learning effect from pre- to post-test. The responsible examiners however ensured not to give participating players any indication of what variables were in focus for the study. For those few variables not normally distributed or with non-homogeneous variance, non-parametric tests were not performed, as the mixed design repeated measures ANOVA was assumed to be a robust test to violations of these assumptions[118].

5.0 Conclusion

In the present study, an association between increases in hip abductor strength and reductions in knee abduction moment and knee valgus angle was not found, contrary to the study hypothesis. Due to lack of increase in hip abductor strength in the intervention group compared to the control group, the present study cannot however refute that an association exists between increased hip abductor strength and reduced knee valgus. This study could however support the notion that solely focusing on strengthening the hip abductors is insufficient to reduce knee valgus in jump tasks.

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