Positive influence of neuromuscular training on knee injury risk factors during cutting and landing tasks in elite youth female handball players

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Abstract

Anterior cruciate ligament (ACL) ruptures are frequent in the age group of 15–19 years, particularly for female athletes. Although injury-prevention programs effectively reduce severe knee injuries, little is known about the underlying mechanisms and changes of biomechanical risk factors. Thus, this study analyzes the effects of a neuromuscular injury-prevention program on biomechanical parameters associated with ACL injuries in elite youth female handball players. In a nonrandomized, controlled intervention study, 19 players allocated to control ($n = 12$) and intervention ($n = 7$) group were investigated for single- and double-leg landings as well as unanticipated side-cutting maneuvers before and after a 12-week study period. The lower-extremity motion of the athletes was captured using a three-dimensional motion capture system consisting of 12 infrared cameras. A lower-body marker set of 40 markers together with a rigid body model, including a forefoot, rearfoot, shank, thigh, and pelvis segment in combination with two force plates was used to determine knee joint angles, resultant external joint moments, and vertical ground reaction forces. The two groups did not differ significantly during pretesting. Only the intervention group showed significant improvements in the initial knee abduction angle during single leg landing ($p = 0.038$: $d = 0.518$), knee flexion moment during double-leg landings ($p = 0.011$; $d = -1.086$), knee abduction moment during single ($p = 0.036$; $d = 0.585$) and double-leg landing ($p = 0.006$; $d = 0.944$) and side-cutting ($p = 0.015$;$d = 0.561$) as well as vertical ground reaction force during double-leg landing ($p = 0.004$; $d = 1.482$). Control group demonstrated no significant changes in kinematics and kinetics. However, at postintervention both groups were not significantly different in any of the biomechanical outcomes except for the normalized knee flexion moment of the dominant leg during single-leg landing. This study provides first indications that the implementation of a training intervention with specific neuromuscular exercises has positive impacts on biomechanical risk factors associated with ACL injury risk and, therefore, may help prevent severe knee injuries in elite youth female handball players.

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Supplementary Information

The online version of this article (https://doi.org/10.1007/s12662-022-00851-w) contains supplementary material, which is available to authorized users.

Introduction

In team handball, high incidences of noncontact injuries were reported in all age groups (Laver, Luig, Achenbach, Myklebust, & Karlsson, 2018). Lower extremities are thereby the most common injury location, accounting for more than 50% of the overall injury rate in youth athletes. Knee injuries, mainly anterior cruciate ligament (ACL) ruptures, are the most frequent severe injury in the age group of 15–19 years, and it is widely known that females bear an increased risk of ACL injuries, which increases during adolescence (Bram, Magee, Mehta, Patel, & Ganley, 2021). Increased knee valgus angles and moments among women compared to men have been repeatedly observed throughout multiple landing tasks and cutting maneuvers, reflecting sex specific differences that are likely to contribute to the etiology of ACL injuries (Kernozek, Torry, Van Hoof, Cowley, & Tanner, 2005; Parsons, Coen, & Bekker, 2021; Patel et al., 2021). In female youth athletes, dynamic knee valgus is the preliminary mechanism of ACL injuries. Bedo et al. (2021) found that unanticipated side-cutting (SC) impacted knee kinematics by decreasing the flexion angle in the nondominant leg and increased valgus angles bilaterally. Empirical evidence also suggests that increased knee valgus angles during single leg landings and cutting movements (Bedo et al., 2020) result in an increased injury risk. Furthermore, Almonroeder, Garcia, and Kurt (2015) concluded that tasks which do not allow a subject to preplan their movement strategy promote knee mechanics which may increase an athlete's risk of injury.

Prevention programs for ACL injuries frequently based on neuromuscular exercises have been shown to be effective and, hence, are well published and a common method to reduce the number of severe knee injuries (Myklebust et al., 2003). However, most of these studies have focused on the injuries of adult elite or youth male team players (Achenbach et al., 2018; Myer, Ford, Palumbo, & Hewett, 2005; Wedderkopp, Kaltoft, Lundgaard, Rosendahl, & Froberg, 1999). Evidence regarding benefits for the high-risk injury group of elite youth female handball players mainly focusses on the effects of intervention programs on injury rates (Cadens Roca, Planas, Matas, & Peirau, 2021; Olsen, Myklebust, Engebretsen, Holme, & Bahr, 2005). Consequently, there is little evidence about the underlying changes in biomechanical risk factors following targeted injury prevention programs, which result in reduced risks of suffering from an ACL injury.

Therefore, the purpose of this study was to analyze the effects of an injury-prevention program for elite youth female handball players that includes neuromuscular exercises to reduce biomechanical risk factors for ACL injuries. Based on previous findings, it was hypothesized that frequent neuromuscular exercises improve kinematics and kinetics associated with ACL injury risk during landing and cutting movements.

Methods

A nonrandomized, controlled cohort repeated-measures intervention study was applied to determine the effects of an injury-prevention program based on frequent neuromuscular exercises on biomechanics in landing and cutting movements associated with ACL-injury risk.

Availability of data and material
The data that support the finding of this study are not publicly available due to privacy or ethical restrictions but are available from the corresponding author on reasonable request.

Code availability
Not applicable.

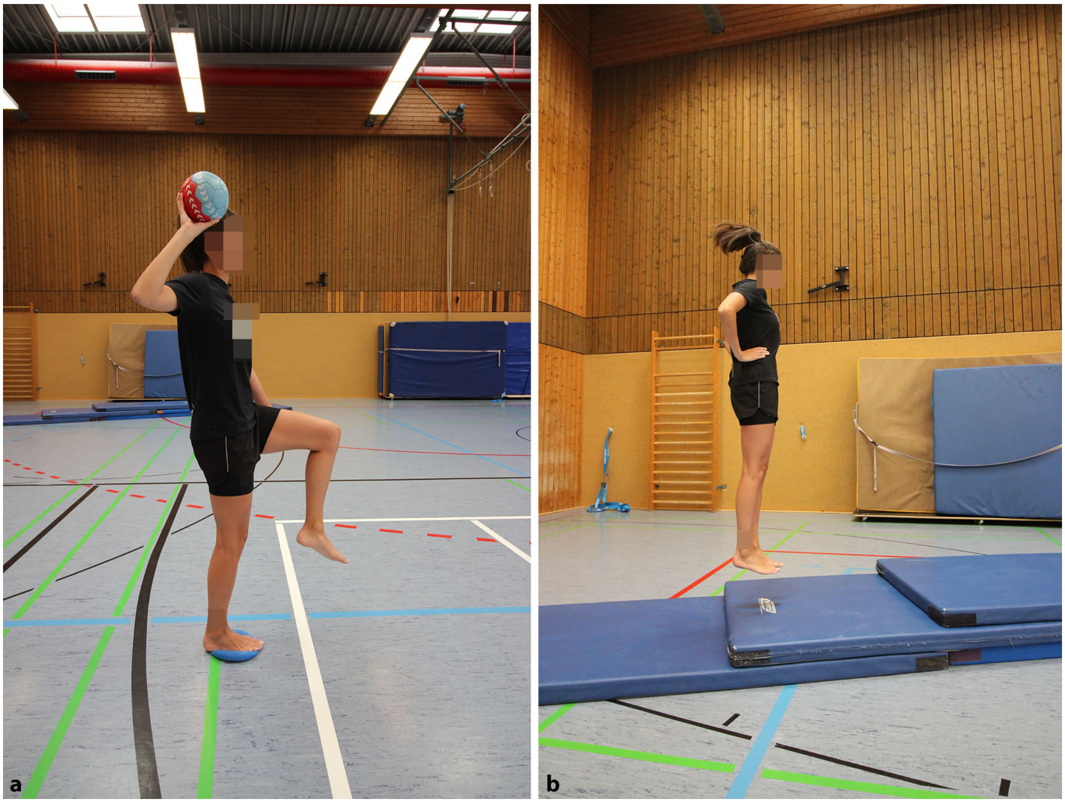

Fig. 1 ◀ Module 1 (**a**) including variations of proprioceptive exercises: single-leg stabilization on unstable surface; Module 2 (**b**) including variations of single- and double-leg plyometric exercises

A total of 25 elite youth female handball players (age 16.3 ± 1.2 years, height 172 ± 6 cm, weight 70 ± 10 kg) were recruited from two teams of a handball club of the first national league and volunteered to participate in this study. All participants received detailed instructions about the study design and the planned study protocol. Players were excluded if they had suffered a lower extremity injury in the 6 weeks prior to the study phase. However, this was not the case for any of the 25 players. The study was conducted according to the ethical requirements of the Declaration of Helsinki and was approved by the local ethical committee (No. 2018-03). The study consisted of a specific experimental protocol which was completed by two separate groups (intervention and control) at two testing sessions prior to (pretest) and after (posttest) an intervention phase. Because of practical reasons, we had to assign players into the intervention or control group based on a planned team affiliation. This means that all eligible players usually attend the same four training sessions during a week. In addition, in a fifth session the coaching staff divided the players into two groups according to a planned team affiliation for the upcoming match-day to train team-specific tactical behavior. During the intervention phase, this separation had been fixed to steadily allow a separation of intervention and control group.

During the intervention phase, players of the intervention group (IG) completed a neuromuscular training program during the warm-up phase of their usual training. At the same time, the control group (CG) completed their usual handball-specific training to ensure comparable training load (usually five sessions per week, 120 min duration of each training session, same content except the warm-up program).

The injury-prevention program was comprised of 30–40 min training exercises once a week during the competition period from September to December 2019 and was instructed by the study coordinator. Instructions were primarily presented with an external focus of attention, as it is suggested that this focus strategy results in reduced injury risk and benefits the rehabilitation of ACL injuries because of enhanced motor learning (Benjaminse et al., 2015; Singh, Gokeler, & Benjaminse, 2021). A total of ten training sessions were conducted during a 12-week period including 2 weeks of holiday without regular training sessions. Due to an illness of the study coordinator during the fifth intervention week, two intervention sessions were performed in week six. The prevention program was based on neuromuscular exercises and consisted of four different modules, according to previously published intervention studies (Achenbach et al., 2018; Büsch, Pabst, Mühlbauer, Ehrhardt, & Granacher, 2015) and scientific recommendations (Fort-Vanmeerhaeghe, Romero-Rodriguez, Lloyd, Kushner, & Myer, 2016). The program included four modules of (1) proprioceptive exercises, (2) plyometric exercises, (3) jump and landing exercises, and (4) strength exercises for the core muscles. Each module comprised several exercises and variations, which progressed from easy to more difficult and were adjusted according to each player's progression (**Figs. 1 and 2**; **Table 1**). Most exercises have already been shown to prevent injuries of

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Abstract

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Keywords

Anterior cruciate ligament · Injury · Prevention · Biomechanics · Motion analysis · Effect size

the lower extremities (Achenbach et al., 2018; Mandelbaum et al., 2005; Myklebust et al., 2003) and could be executed with as little additional equipment as possible. A pre-established compliance criterion required that each participant be present for at least 70% (7 of 10) of the training sessions to be included in the statistical analysis. Upon completion of the pretest, one athlete of the control group moved and could, therefore, not be included in posttest measurement. After finishing the pretest but before the first intervention session, two athletes of the intervention group suffered an injury and did not meet the pre-established compliance criterion. Additionally, 2 weeks before the posttest, two players of the control group received an injury and could not be included for the measurements. Unfortunately, due to problems during posttest data acquisition (missing force plate data), one athlete of the control group had to be excluded from further data analysis. Consequently, data of 12 subjects of the intervention and 7 of the control group were considered for statistical data analysis.

Each testing session started with a standardized warm-up consisting of 10 min light to moderate handball-specific movements. The laboratory-based test battery included double-leg drop vertical landings (DLL), single-leg drop landings (SLL), and an unanticipated side-cutting task, performed with both legs, respectively. All landing and cuttings tasks were performed on two 0.9 × 0.6 m force plates (AMTI©, Watertown, MA, USA) sampled at 1000 Hz. A rest period of at least 30 s was provided between repetitions, and at least a 2 min rest was provided between tasks.

For the DLL, participants stood on a 30 cm high wooden box and were instructed to drop straight down off the box, land on both force plates, and jump vertically as high as possible (Peebles, Dickerson, Renner, & Queen, 2020). SLL were performed identically with landing performed on just one force plate and without a subsequent jump. Arm movement was restricted with hands fixed at the hip during either task. Participants were asked to practice both landing tasks prior to data collection to reduce unsuccessful trials. If a trial was performed incorrectly (e.g., not landing on the force plates), it was repeated until three successful trials for both legs were completed. Approaches to the unanticipated SC were performed from a distance of 3.5 m to the force plates. After reaching a light barrier (Fitlight™, VISUS GmbH, Herrenberg, Germany), participants had to react according to a flashing light indicating the movement direction of the cutting maneuver. Athletes were asked to perform the SC as fast and as similiar as possible to a playing situation.

The lower-extremity motion of the athletes was captured using a three-dimensional motion capture system consisting of 12 infrared cameras (120 Hz, Qualisys©, Göteborg, Sweden), which was time-synchronized to the force plates. We used a lower-body marker set of 40 markers and a rigid body model, including a forefoot, rearfoot, shank, thigh, and pelvis segment according to Willwacher, Kurz, Menne, Schrödter, and Brüggemann (2016) to determine knee joint angles, as well as resultant external joint moments. Marker trajectory and ground reaction force data were filtered with a fourth-order digital Butterworth filter with a cutoff frequency of 20 Hz in order to avoid impact-related artifacts in lower extremity joint moments (Mai & Willwacher, 2019). A customized MATLAB routine (MathWorks©, Natick, MA, USA) was used to calculate kinematic and kinetic parameters by a three-dimensional inverse dynamics model (Sanno, Willwacher,

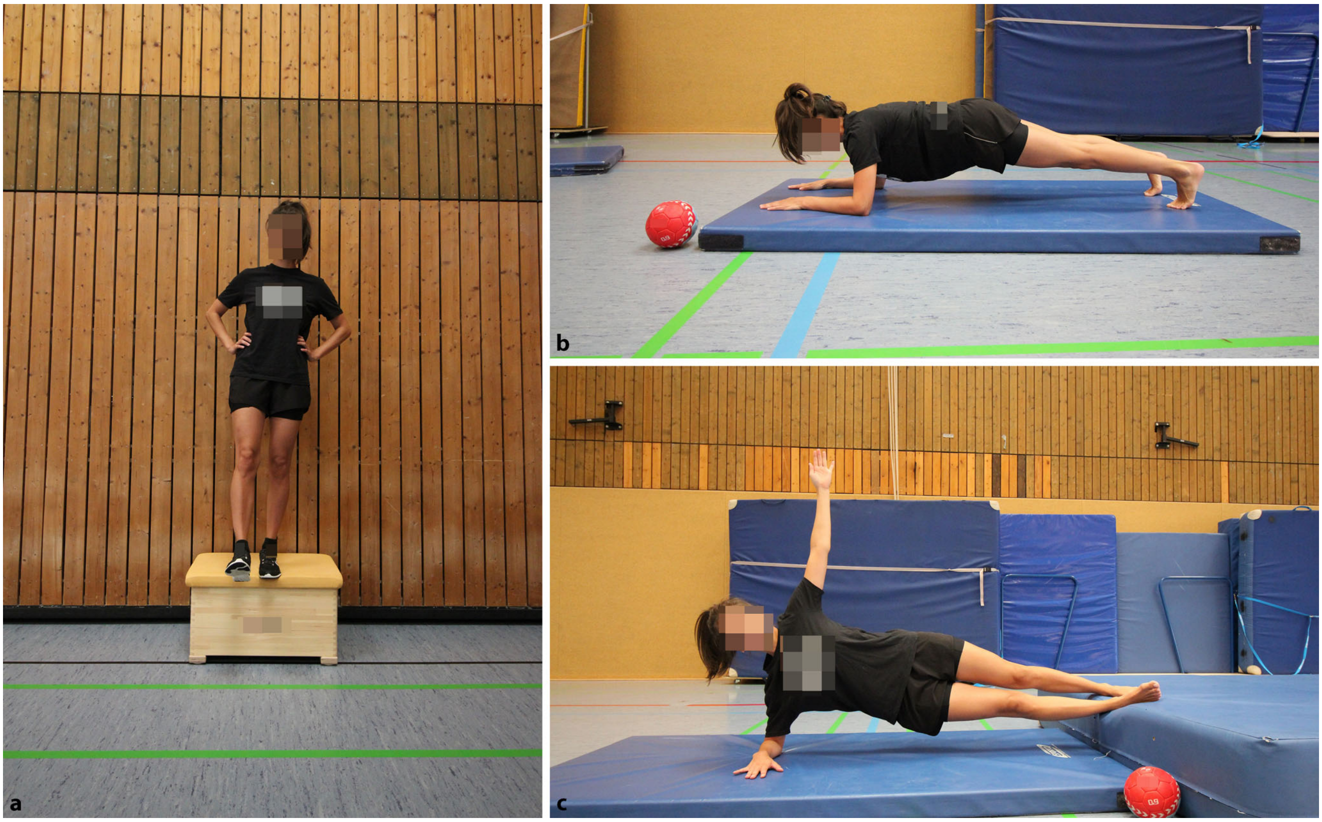

Fig. 2 ▲ Module 3 (**a**) including variations of single- and double-leg multidirectional jump and landing exercises; Module 4 (**b**, **c**) including variations of strength exercises for the core muscles

Epro, & Brüggemann, 2018). Knee flexion–extension, abduction–adduction, and internal–external rotation angles were calculated and served as kinematic variables. Kinetics included knee flexion–extension moment, dynamic knee valgus moment, and vertical vGRF. Body mass was used to normalize all kinetic parameters. Joint torques were expressed in the anatomical coordinate systems of the respective proximal segments. Stance phases for all tasks were defined as the interval from foot strike on the force plate to take-off and were calculated using a threshold of 20 N of the smoothed vGRF component. Kinematic parameters were determined for two instances: at initial contact (IC) and at the maximum within the first 100 ms of the stance phase. For kinetic parameters, the maximum value within this time window was determined. We considered the first 100 ms after IC because reconstructions of injury situations suggest that ACL injuries usually occur within this time window (Krosshaug et al., 2007). For each task and leg, the average of the three trials was calculated for each parameter and considered for further analysis (Peebles et al., 2020). It has been shown that between-session reliability of kinematic and kinetic data can be considered high for landing and cutting movements (Dos'Santos, Thomas, Comfort, & Jones, 2021).

Statistical means and SD for each outcome were calculated for the dominant and nondominant limb separately. Normality was controlled for all variables using a Shapiro–Wilks test. Homogeneity of the pretest values between the two groups was analyzed via independent *t* tests. Thereby, there were no significant differences for the control and intervention group for any of the kinematic or kinetic parameters during the pretest (Supplement S1). We therefore analyzed the within-subject effects from pre- to posttest by using paired sample *t* tests. In addition, to test whether the intervention resulted in significantly greater improvements or not compared to controls, a between-group comparison at posttest was done by performing independent sample *t* tests. Statistical significance was defined with α set at < 0.05. Magnitudes of differences were assessed using Cohen's d effect sizes (ES) and interpreted as small (0.25), medium (0.5), and large (1.0; Rhea, 2004). Statistical analyses were performed using R Software for statistical computing (RCoreTeam, 2014).

Results

Both groups were similar in age (IG: 15.8 ± 0.4 years; CG: 16.0 ± 1.3), height (IG: 172.7 ± 4.8 cm; CG: 174.3 ± 7.3 cm) and weight (IG: 71.5 ± 10.2 kg; CG: 68.5 ± 10.4 kg). A descriptive overview of pre- and posttest data for the landing and cutting tasks is presented in ◘ **Table 2** (IG) and ◘ **Table 3** (CG). ◘ **Table 4** represents the between-group comparison of posttest values.

Subjects of the intervention group showed significant changes by time of the kinematic parameters for initial knee

Table 1 Exercise modules, examples and progression model

Exercise module	Exercise example	Exercise progression
Proprioceptive exercises	Standing on one leg with variations of arm position or additional tasks like throwing and catching a ball	1. Standing on a stable surface (hall floor) 2. Standing on a slightly unstable surface (e.g., a rubber ring, ◘ **Fig. 1a**) 3. Standing on an unstable surface (e.g., a soft floor mat) 4. Standing on an unstable surface with eyes closed or being destabilized by a partner
Plyometric exercises	Uni- and multidirectional double- and single-leg plyometric jumps with a focus on short ground contact time	1. Unidirectional double-leg jumps 2. Multidirectional double-leg jumps 3. Uni- and multidirectional single-leg jumps 4. Uni- and multidirectional double- and single-leg jumps on a slightly unstable surface (e.g., a stair of mats, ◘ **Fig. 1b**)
Jump and landing exercises	Double- and single-leg drop and rebound jump landings	1. Isolated double-leg drop landings (25–40 cm height) 2. Isolated single-leg drop landings (25–40 cm height) 3. Isolated double- and single-leg drop with a rebound jump and second landing 4. Series of double- and single-leg drop and rebound jump landings in horizontal direction over an obstacle (e.g., a box, ◘ **Fig. 2a**)
Strength exercises	Core exercises: variations of plank or side plank and sit-ups	1. "Standard" core exercises 2. Core exercises with dynamic disturbances like lifting one leg or arm 3. Core exercises with dynamic disturbances and one part of the body placed on an unstable surface (e.g., a soft floor mat, ◘ **Fig. 2c**)

abduction angle of the dominant leg during SLL ($p = 0.038$, $d = 0.518$) with increased abduction angles at posttest (Pre: 1.1 ± 4.0°, Post: −1.3 ± 5.1°; abduction is denoted as negative and a valgus position, adduction is denoted as positive and a varus position). All other kinematic parameters of the intervention group did not show any significant changes. Kinetic parameters of the dominant leg showed significant changes in the knee flexion moment during DLL, knee abduction moment during DLL, SLL, and SC as well as vGRF of the during DLL. The nondominant leg showed significant changes by time solely for vGRF during SLL. Detailed information about the significant effects of the intervention on kinetic parameters is presented in ◘ **Figs. 3**, **4**, and **5**. Descriptive analysis of intervention group data also revealed that kinetic parameters during all tasks showed decreased joint moments and vGRF from pre- to posttest, except for the knee abduction moment of the nondominant leg during DLL and SLL (◘ **Table 2**). The control group demonstrated no significant changes in kinematic and kinetic parameters from pre- to posttest (◘ **Table 3**). Between-group comparison of the posttest values showed a significant effect of group for the normalized knee flexion moment of the dominant leg during SLL only, while all other comparisons resulted in nonsignificant effects (◘ **Table 4**).

Discussion

The presented neuromuscular training program designed for the prevention of ACL-injuries provided improvements of landing and cutting biomechanics in elite youth female handball players. Athletes who underwent the 12-week protocol, including ten training sessions, were primarily able to reduce knee valgus moments compared to their pretraining intervention values and an untrained control group. The improvements of the intervention group were statistically significant and practically relevant with medium to large effect sizes. This result is in line with findings of Myer et al. (2005), who found reduced knee valgus moments after completing a 6-week intervention, including three training sessions per week and a duration of up to 90 min.

Based on the results of the recent study, relevant changes of kinetic parameters are primarily observable for the dominant leg of the athletes. On the nondominant side nonsignificant decreases of joint moments were found for knee flexion during DLL, SLL, and SC as well as knee abduction during SC. Solely, significant decreases of vGRF during SLL were found. Nevertheless, based on nonsignificantly decreased vGRF for the nondominant leg during DLL and SC we conclude in concordance to Hewett, Stroupe, Nance, and Noyes (1996) that these results lead to a reduced injury-risk for ACL ruptures.

Our observation that mainly the dominant leg is positively affected by the intervention program reveals some important recommendations about leg dominance. For example, Schmidt, Nolte, Terschluse, and Jaitner (2020) found that performing under fatigued conditions results in impaired kinematics of the nondominant leg during landing and cutting tasks of elite youth female handball players. Hosseini, Daneshjoo, Sahebozamani, and Behm (2021) likewise found that the dominant leg had significantly more flexion, less valgus and lower tibia rotation compared to the nondominant leg in predictable and prefatigue conditions. In addition, during unanticipated and fatigued conditions the dominant limb again demonstrated greater knee flexion, lower knee valgus, and less tibia rotation. In conclusion, there may be an increased risk of injury with the nondominant (Hosseini et al., 2021). Bedo et al. (2021) also detect lower knee flexion angle during unanticipated cutting movements compared with anticipated for the nondominant leg, as well as increased knee abduction for both the dominant and nondominant leg. In this study, the nondominant leg showed higher knee abduction during the unanticipated cutting compared with the anticipated. The authors conclude that unanticipated cutting impacts knee kinematics and potentially

Table 2 Pre- to postchanges in double-leg landing (DLL), single-leg landing (SLL) and side-cutting (SC) for the dominant and nondominant leg of the intervention group

Test	Variable	Dominant leg						Nondominant leg					
		Pre		Post		*p*	Cohen's d	Pre		Post		*p*	Cohen's d
		Mean	SD	Mean	SD			Mean	SD	Mean	SD		
DLL	kfin [°]	28.5	8.1	31.5	6.7	0.298	−0.404	28.5	4.6	25.9	4.5	0.100	0.575
	kfmax [°]	74.4	6.4	75.2	6.0	0.770	−0.128	72.7	6.5	72.8	4.8	0.948	−0.024
	krin [°]	1.8	9.0	1.5	5.8	0.925	0.026	−1.3	3.7	−2.6	5.4	0.473	0.282
	krmax [°]	12.1	6.5	11.1	4.5	0.653	0.179	10.5	4.5	8.7	5.7	0.385	0.345
	kabin [°]	0.3	3.8	0.5	5.5	0.869	−0.036	2.6	3.3	0.6	6.7	0.161	0.257
	kabmax [°]	−7.9	5.4	−9.3	6.6	0.282	0.217	−8.5	3.6	−9.0	8.1	0.850	0.073
	kfmom [Nm/kg]	−1.9	0.4	−1.5	0.3	0.011*	−1.086	−1.7	0.4	−1.5	0.3	0.168	−0.572
	kabmom [Nm/kg]	0.2	0.2	0.0	0.1	0.006*	0.944	0.5	0.2	0.6	0.5	0.619	−0.187
	vGRF [N/kg]	15.2	2.5	12.1	1.5	0.004*	1.482	15.8	3.0	15.1	2.7	0.451	0.232
SLL	kfin [°]	27.9	5.7	26.4	5.2	0.558	0.258	16.8	6.1	17.1	5.9	0.757	−0.057
	kfmax [°]	58.5	4.8	57.3	3.5	0.522	0.296	56.9	5.3	59.2	5.3	0.192	−0.436
	krin [°]	2.2	6.5	4.0	6.0	0.347	−0.275	0.2	4.9	−0.8	5.8	0.650	0.175
	krmax [°]	14.0	7.6	14.6	5.6	0.659	−0.086	10.6	3.4	9.1	5.4	0.257	0.310
	kabin [°]	1.1	4.0	−1.3	5.1	0.038	0.518	1.6	2.6	−0.3	5.7	0.176	0.337
	kabmax [°]	−6.5	4.7	−8.9	6.9	0.169	0.368	−4.4	2.7	−6.0	6.7	0.447	0.308
	kfmom [Nm/kg]	−2.3	0.4	−2.3	0.4	0.984	−0.008	−2.2	0.4	−2.0	0.4	0.138	−0.509
	kabmom [Nm/kg]	0.2	0.3	0.1	0.2	0.036*	0.585	0.1	0.1	0.3	0.4	0.225	−0.376
	vGRF [N/kg]	19.9	3.6	19.5	3.1	0.650	0.126	28.3	4.1	26.1	3.6	0.004*	0.572
SC	kfin [°]	28.3	5.3	27.1	5.0	0.619	0.235	29.1	7.4	26.1	5.3	0.077	0.433
	kfmax [°]	58.7	4.6	57.3	3.5	0.494	0.323	59.2	5.0	57.0	3.9	0.104	0.480
	krin [°]	2.7	6.4	4.4	5.8	0.337	−0.285	5.3	9.0	3.0	8.0	0.291	0.263
	krmax [°]	14.4	7.5	14.8	5.6	0.777	−0.055	14.1	7.6	13.0	7.3	0.425	0.153
	kabin [°]	1.0	4.1	−1.4	5.0	0.056	0.510	−0.3	4.8	−0.7	7.4	0.832	0.064
	kabmax [°]	−7.2	5.0	−9.1	6.6	0.344	0.314	−8.1	4.6	−6.6	6.7	0.435	−0.258
	kfmom [Nm/kg]	−2.4	0.3	−2.3	0.4	0.663	−0.140	−2.5	0.3	−2.3	0.4	0.186	−0.663
	kabmom [Nm/kg]	0.3	0.4	0.1	0.2	0.015*	0.561	0.7	0.4	0.7	0.5	0.614	0.150
	vGRF [N/kg]	19.3	3.1	18.8	2.5	0.628	0.163	19.6	2.0	19.1	2.1	0.502	0.261

Knee flexion moment as well as knee abduction moment (representing a valgus moment) values are denoted negative because of the used segmental coordinate system

kfin initial knee flexion angle, ***kfmax*** maximum knee flexion angle, ***krin*** initial internal rotation angle, ***krmax*** maximum internal rotation angle, ***kabin*** initial knee abduction angle, ***kabmax*** maximum knee abduction angle, ***kfmom*** normalized maximum knee flexion moment, ***kabmom*** normalized maximum knee abduction moment, ***vGRF*** normalized maximum vertical ground reaction force

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Test	Variable	Dominant leg						Nondominant leg					
		Pre		Post		*p*	Cohen's d	Pre		Post		*p*	Cohen's d
		Mean	SD	Mean	SD			Mean	SD	Mean	SD		
DLL	kfin [°]	28.9	6.3	32.6	6.0	0.212	−0.588	29.7	4.8	30.3	5.7	0.736	−0.125
	kfmax [°]	76.8	6.5	76.7	5.6	0.946	0.018	76.1	6.8	76.4	6.2	0.819	−0.050
	krin [°]	0.7	5.4	2.3	3.8	0.462	−0.325	−2.8	6.9	1.2	7.3	0.088	−0.567
	krmax [°]	9.4	5.3	11.3	7.3	0.528	−0.295	7.8	7.0	11.9	7.6	0.188	−0.562
	kabin [°]	−0.2	6.9	1.6	3.1	0.555	−0.340	1.2	7.1	3.8	4.8	0.519	−0.428
	kabmax [°]	−10.3	3.9	−7.2	5.0	0.317	−0.696	−9.9	7.0	−6.1	6.9	0.268	−0.544
	kfmom [Nm/kg]	−1.7	0.4	−1.8	0.2	0.754	0.171	−1.8	0.4	−1.8	0.5	0.871	−0.075
	Kabmom [Nm/kg]	0.4	0.2	0.2	0.3	0.120	0.771	0.5	0.4	0.5	0.3	0.976	−0.008
	vGRF [N/kg]	12.5	1.6	13.6	1.6	0.135	−0.704	14.8	3.6	15.0	3.1	0.860	−0.071
SLL	kfin [°]	23.5	11.2	21.9	6.1	0.613	0.146	22.0	8.8	22.4	10.7	0.699	−0.038
	kfmax [°]	54.8	8.8	54.7	5.8	0.975	0.008	57.1	3.6	54.9	6.1	0.227	0.405
	krin [°]	2.2	6.1	4.7	3.5	0.145	−0.418	−2.1	5.0	2.2	9.5	0.361	−0.580
	krmax [°]	11.2	5.0	13.5	5.3	0.233	−0.438	9.7	5.5	13.1	7.4	0.338	−0.511
	kabin [°]	−1.9	6.0	−0.7	2.7	0.635	−0.267	−0.3	6.9	1.7	2.3	0.422	−0.346
	kabmax [°]	−8.4	5.0	−4.8	4.1	0.190	−0.802	−7.8	6.0	−3.2	4.1	0.085	−0.868
	kfmom [Nm/kg]	−2.6	0.7	−2.2	0.2	0.159	−0.619	−2.6	0.6	−2.2	0.6	0.106	−0.700
	Kabmom [Nm/kg]	0.2	0.4	0.1	0.1	0.668	0.286	0.2	0.3	0.3	0.3	0.441	−0.286
	vGRF [N/kg]	24.7	5.4	23.3	5.2	0.236	0.263	27.7	8.6	24.5	5.2	0.071	0.226
SC	kfin [°]	29.0	11.3	27.1	3.9	0.570	0.133	31.2	6.6	29.9	6.9	0.642	0.193
	kfmax [°]	58.0	5.1	58.3	5.8	0.872	−0.042	58.6	3.3	59.3	3.6	0.447	−0.219
	krin [°]	3.8	6.8	5.7	5.1	0.496	−0.309	0.4	6.6	5.6	10.7	0.263	−0.579
	krmax [°]	13.0	5.0	14.7	6.5	0.428	−0.285	11.8	6.5	15.3	9.0	0.337	−0.435
	kabin [°]	−3.1	7.6	−0.9	2.9	0.508	−0.396	−0.6	7.3	1.0	2.5	0.532	−0.271
	kabmax [°]	−10.3	6.0	−6.1	2.8	0.143	−0.870	−9.7	5.7	−4.9	5.0	0.065	−0.885
	kfmom [Nm/kg]	−2.7	0.7	−2.4	0.4	0.139	−0.528	−2.6	0.3	−2.4	0.3	0.275	−0.485
	Kabmom [Nm/kg]	0.5	0.8	0.3	0.3	0.403	0.108	0.6	0.7	0.5	0.4	0.582	0.104
	vGRF [N/kg]	20.9	2.4	20.0	2.6	0.177	0.390	20.2	2.6	19.7	2.6	0.343	0.199

Knee flexion moment as well as knee abduction moment (representing a valgus moment) values are denoted negative because of the used segmental coordinate system

kfin initial knee flexion angle, ***kfmax*** maximum knee flexion angle, ***krin*** initial internal rotation angle, ***krmax*** maximum internal rotation angle, ***kabin*** initial knee abduction angle, ***kabmax*** maximum knee abduction angle, ***kfmom*** normalized maximum knee flexion moment, ***kabmom*** normalized maximum knee abduction moment, ***vGRF*** normalized maximum vertical ground reaction force

Table 4 Between-group comparison of posttest values of double-leg landing (DLL), single-leg landing (SLL) and side-cutting (SC) for the dominant and nondominant leg

Test	Variable	Dominant leg		Nondominant leg	
		p	Cohen's d	*p*	Cohen's d
DLL	kfin [°]	0.993	−0.004	0.237	−0.645
	kfmax [°]	0.710	−0.208	0.219	−0.609
	krin [°]	0.638	−0.225	0.598	−0.281
	krmax [°]	0.974	0.017	0.580	−0.29
	kabin [°]	0.778	−0.124	0.478	−0.292
	kabmax [°]	0.213	−0.536	0.540	−0.283
	kfmom [Nm/kg]	0.693	0.208	0.268	0.539
	Kabmom [Nm/kg]	0.186	−0.728	0.583	0.255
	vGRF [N/kg]	0.368	−0.455	0.577	−0.293
SLL	kfin [°]	0.725	−0.17	0.109	−0.896
	kfmax [°]	0.582	−0.269	0.225	−0.664
	krin [°]	0.752	−0.142	0.261	−0.617
	krmax [°]	0.962	−0.027	0.362	−0.494
	kabin [°]	0.576	−0.244	0.258	−0.525
	kabmax [°]	0.462	−0.342	0.427	−0.381
	kfmom [Nm/kg]	0.035*	0.985	0.328	0.575
	Kabmom [Nm/kg]	0.116	−0.965	0.446	0.338
	vGRF [N/kg]	0.065	−0.975	0.961	0.025
SC	kfin [°]	0.131	0.813	0.262	−0.659
	kfmax [°]	0.319	0.572	0.068	−1.003
	krin [°]	0.758	−0.135	0.474	−0.403
	krmax [°]	0.670	0.208	0.244	−0.643
	kabin [°]	0.717	−0.157	0.315	−0.426
	kabmax [°]	0.132	−0.684	0.294	−0.472
	kfmom [Nm/kg]	0.564	−0.255	0.427	0.419
	Kabmom [Nm/kg]	0.690	−0.173	0.995	0.003
	vGRF [N/kg]	0.113	−0.956	0.517	0.353

Knee flexion moment as well as knee abduction moment (representing a valgus moment) values are denoted negative because of the used segmental coordinate system
kfin initial knee flexion angle, ***kfmax*** maximum knee flexion angle, ***krin*** initial internal rotation angle, ***krmax*** maximum internal rotation angle, ***kabin*** initial knee abduction angle, ***kabmax*** maximum knee abduction angle, ***kfmom*** normalized maximum knee flexion moment, ***kabmom*** normalized maximum knee abduction moment, ***vGRF*** normalized maximum vertical ground reaction force

Abbreviations

ACL	Anterior cruciate ligament
CG	Control group
DLL	Double-leg drop vertical landing
ES	Effect size
IG	Intervention group
kabin	Initial knee abduction angle
kabmax	Maximum knee abduction angle
kabmom	Normalized maximum knee abduction moment
kfin	Initial knee flexion angle
kfmax	Maximum knee flexion angle
kfmom	Normalized maximum knee flexion moment
krin	Initial internal rotation angle
krmax	Maximum internal rotation angle
SC	Side-cutting
SLL	Single-leg drop landing
vGRF	Vertical ground reaction force

positioned the joint at greater risk of injury by decreasing the flexion angle in the nondominant leg and increasing the joint valgus bilaterally (Bedo et al., 2021).

These findings highlight an important role of the nondominant leg within preventive strategies. Thus, targeted training of the nondominant leg and with respect to fatigued conditions should necessarily be incorporated within ACL injury prevention strategies to achieve a comprehensive reduction of injury risk. Especially, this is important for targeted interventions in female athletes because of anatomical gender differences that are likely to contribute to the etiology of ACL injuries (Parsons et al., 2021; Patel et al., 2021).

Contrary to previously presented comprehensive intervention programs, our training program solely consisted of 10 sessions within 12 weeks, with each session lasting not more than 40 min. Nevertheless, improvements of kinetic parameters associated with ACL injury risk show medium to large effect sizes (0.561–1.482, **Figs.** 3, 4, and 5). Our findings indicate possible causes for the preventive effects of neuromuscular training interventions to reduce lower-extremity injuries in youth handball found in previous studies (Achenbach et al., 2018; Myklebust et al., 2003; Steffen, Myklebust, Olsen, Holme, & Bahr, 2008). Accordingly, a preventive program, including proprioceptive exercises, plyometric exercises, jump, and landing exercises as well as strength exercises for the core muscles, should be performed during the whole competitive cycle (Cadens Roca et al., 2021; Fort-Vanmeerhaeghe et al., 2016).

This study comprises a few limitations that should be outlined. First, besides the significant within group effects of the intervention group, we also found that between-group comparison at posttest mostly resulted in nonsignificant differences except the normalized knee flexion moment of the dominant leg during SLL. The mainly nonsignificant between-group effects at posttest are most likely the result of the small sample size and large variations between the two groups. In addition, a possible dependency between both legs may have affected between-group interaction effects. Future studies with larger sample sizes need to account for the potential effects of a between-leg dependency by using a repeated measures mixed analysis of variance (ANOVA) approach. However, attaining access to

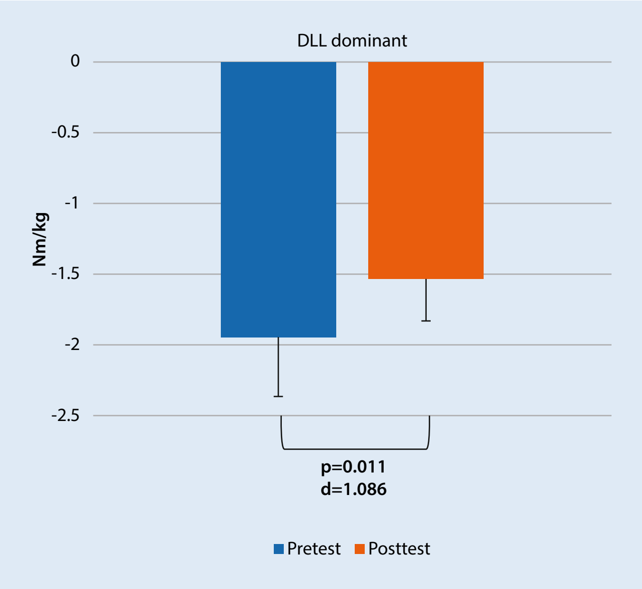

Fig. 3 ▲ Knee flexion moment was significantly reduced on the dominant leg during DLL. Flexion values are denoted negative because of the used segmental coordinate system

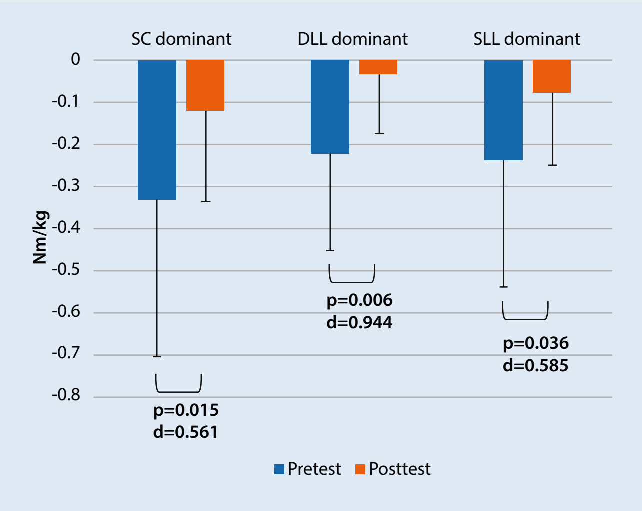

Fig. 4 ▲ Significant changes of knee abduction–adduction moments. Abduction is denoted as negative representing a valgus moment while adduction is denoted as positive and a varus moment

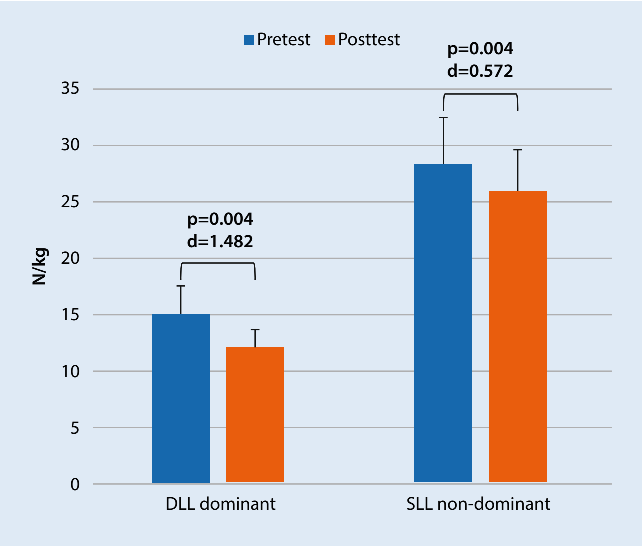

Fig. 5 ◀ Significant changes of vGRF

a larger number of elite youth female athletes competing at a comparable (national) level is difficult and was not possible during this study. Therefore, the findings of this study should be confirmed in a larger population including different age groups, gender, playing level and an extended intervention period and the results of this study might be judged carefully and be seen as preliminarily.

Second, the approach speed of the unanticipated cutting task was not standardized, which may have affected the biomechanical outcomes. However, as the athletes were asked to perform the SC as fast and as close as possible to a playing situation, we assume that the outcomes reflect a real-world situation.

Third, we assume that the comparatively short duration of the preventive exercises (< 40 min) allows the implementation of the program for daily or weekly routine, we did not analyze any implementation measures that might enhance future implementation or increase compliance. Therefore, efforts should be made to involve all stakeholders (athletes, trainers, physiotherapists, officials) to ensure that these suggestions can be effectively applied in a real-world context (Møller, Ageberg, Bencke, Zebis, & Myklebust, 2018). There was no direct training load monitoring. Nevertheless, both groups were part of the same club squad, competing on the same level, were following similar technical/tactical training, with the same number of training sessions per week, shared the same staff of trainers, and did not perform any additional athletic training. Hence, we conclude that the overall training load experienced by the intervention and control group was comparable. Finally, the missing of a blinded randomization might be considered as another limitation. Nevertheless, due to the affiliation of the athletes to the same training group with only one different training session and matchplay per week during the intervention period we assume that the findings indicate how neuromuscular training affects biomechanical parameters in landing and cutting tasks and are suitable to prevent ACL injuries in elite youth female handball players.

Conclusions

This study provided preliminary evidence that the implementation of a training intervention with specific neuromuscular exercises has positive impacts on biomechanical risk factors associated with anterior cruciate ligament injury risk (primarily reduced knee valgus moments of the dominant leg) and, therefore, may help prevent severe knee injuries in elite youth female handball players. Future studies with larger sample sizes are needed to confirm our preliminary results. Neuromuscular intervention protocols with a more targeted focus on the nondominant leg should also be considered.

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Declarations

Conflict of interest. M. Schmidt, K. Nolte, B. Terschluse, S. Willwacher, and T. Jaitner declare that they have no competing interests.

All procedures performed in studies involving human participants or on human tissue were in accordance with the ethical standards of the institutional research committee (approval No. 2018-03) and with the 1975 Helsinki declaration and its later amendments or comparable ethical standards. All participants received detailed instructions about the study design and the planned study protocol and gave their informed consent.

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