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Influence of a Functional Core Stability Program on Trunk and Knee Joint Biomechanics in Female Athletes During Lateral Movements

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Title: Influence of a functional core stability program on trunk and knee joint biomechanics in female athletes during lateral movements.

Running Head: Core stability training program and lateral movements.

Laboratory where the research was conducted: Institute of Sport and Sport Science, Freiburg, Germany

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Title: Influence of a functional core stability program on trunk and knee joint biomechanics
in female athletes during lateral movements

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Abstract

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3 Trunk positioning has been shown to be associated with knee joint loading during athletic
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5 tasks, especially changes of direction. Quasi-static and conventional core stability (CS)
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7 training did not improve the biomechanics of cutting maneuvers according to reports in the
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9 literature. The purpose of the present study was to test whether a 5-week dynamic and
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11 functional CS training program would improve trunk positioning and knee joint control
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13 during lateral movements.
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17 Nineteen female athletes participated in a longitudinal study, where lateral reactive jumps
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19 (LRJ) and unanticipated cuttings were performed pre and post CS training (15 training
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21 sessions within 5 weeks) while 3D kinematics and kinetics were measured. Additionally, core
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23 endurance and power were evaluated.
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27 CS training increased trunk rotation in the new movement direction ($p = 0.02$) during LRJ.
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29 However, lateral trunk lean was significantly increased during LRJ (from 5.6° to 7°) and
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31 cuttings (from 3.8° to 5.8°) after CS training. Knee joint abduction moment was not
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33 influenced. Finally, core endurance ($p < 0.01$) and core power ($p < 0.001$) were significantly
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35 improved after CS training.
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39 A 5-week dynamic and functional core stability training program improved core muscles
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41 endurance and power. This might explain the better trunk rotation towards the new movement
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43 direction during LRJ, however, it was not effective during unanticipated cuttings.
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47 The practical application of this research will allow strength and conditioning professionals to
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49 setup training programs with simple and relevant exercises to increase the core endurance and
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51 power of trained individuals.
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56 **Keywords:** cuttings, perturbation, trunk lateral lean, knee abduction moment, agility.
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INTRODUCTION

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5 Epidemiological studies have demonstrated that female athletes have a relative higher risk
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7 of sustaining non-contact anterior cruciate ligament (ACL) injuries than male athletes during
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9 sports such as soccer or basketball (1,30). As a countermeasure, preventive neuromuscular
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11 training (PNMT) interventions have been designed to reduce knee joint injuries, especially
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13 ACL ruptures in female athletes (25,32). It has been generally accepted that PNMT
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15 significantly reduces ACL injuries, especially when emphasis is put on specific training
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17 exercises based on strengthening and trunk neuromuscular control (32).
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22 During athletic movements, trunk neuromuscular control is of interest since it influences
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24 trunk load and motion and therefore knee joint loads (12,16). Hewett and Myer (12) proposed
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26 a knee injury model that accounted for both the trunk and hip joints, since increased trunk
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28 lateral lean is reportedly associated with higher external knee abduction moments. Moreover,
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30 a greater lateral trunk position has been shown during anterior cruciate ligament injury
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32 situations in female athletes (14). In a prospective study over 3 years, Zazulak et al. (39)
33
34 demonstrated greater trunk displacement after a sudden force release in athletes who
35
36 subsequently sustained a knee injury. The association between trunk positioning and knee
37
38 joint loads has been investigated during changes of direction or cutting maneuvers, since these
39
40 complex dynamic tasks represent one of the most common playing situations that could lead
41
42 to a non-contact ACL injury (2,20). During cutting maneuvers, increased trunk lateral lean
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44 has been demonstrated to be positively associated with increased knee abduction moments
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46 (8,18,36). Furthermore, increased knee joint loading has been associated with increased trunk
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48 rotation away from the stance limb (8,11). The redirection of the center of mass towards the
49
50 new movement direction seems to be a key factor, as demonstrated by Donnelly et al. (10),
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52 when producing an optimized whole-body kinematics solution to reduce the knee joint
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1 abduction moment. This is also in agreement with David et al. (6), who described a cutting
2 movement strategy with forefoot striking in combination with pre-orientation of the upper
3 body towards the new movement direction to reduce knee joint loads. Accordingly, any
4 improvement in trunk and pelvis positioning during cutting maneuvers is of interest with
5 regard to knee joint loading. Thus, core stability (15,19) should be additionally targeted in
6 existing PNMT interventions aimed at modifying cutting maneuver biomechanics (26).
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15 Although literature has reported that quasi-static core stability (CS) training could
16 significantly reduce the vertical ground reaction force (3) and change leg kinematics and joint
17 moments (28) during drop jump landings, such biomechanical improvements were not found
18 after quasi-static CS training during cutting maneuvers (17). In this latter study, 6 weeks of
19 CS training did not improve core strength, trunk control or knee joint loading during cutting
20 maneuvers relative to resistance training. Moreover, a 6-week dynamic CS program (38) did
21 not influence trunk or pelvis kinematics or knee moments during unanticipated cuttings. In
22 addition, a 4-week training program combining lateral movements and perturbation
23 influenced trunk and pelvis rotation in the same manner as a standard plyometric training, and
24 no influence was found on knee joint moments during unanticipated cuttings (35). Therefore,
25 enhanced dynamic and functional CS training is needed to effectively improve trunk and
26 pelvis control towards the new movement direction during unanticipated cutting maneuvers.
27 However, knee joint loads, and especially knee joint abduction moment, as a relevant
28 parameter associated with knee injury (13), seems not to be influenced by such training,
29 although such training should be beneficial for athletic performance. Indeed, it has been
30 reported in the literature that the endurance (17,33) and strength (29,33) of core muscles was
31 improved and specific athletic performance parameters were increased (29,33,37) after CS
32 programs.
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1 The purpose of the present study was to evaluate the influence of a 5-week dynamic and
2 functional CS training program on trunk and pelvis control and knee joint control during
3 dynamic lateral sporting movements, as well as athletic performance. We tested the
4 hypotheses that i) trunk and pelvis kinematics would be better orientated towards the new
5 movement direction after CS training; ii) the knee joint abduction moment would remain at
6 the same level during cuttings after CS training; and iii) jump performance, agility, core
7 endurance and power would be enhanced following CS training.
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20 **METHODS**

21 **Experimental Approach to the Problem**

22 This study proposed a training intervention over 5 weeks to determine the effects of a
23 dynamic and functional core stability program on cutting biomechanics and athletic
24 performance. Female participants were recruited according to their relative higher risk of
25 sustaining non-contact ACL injuries (1). Although no control group was used in the present
26 study, it was assumed that the results provided by Weltin et al. (35) would constitute reference
27 data to interpret the influence of CS training. The rationale for this was the relatively similar
28 training volume used in their study (three times per week over four weeks) for two relevant
29 training programs, i.e., a modified plyometric training program originally designed by
30 Chimera et al. (4) and a plyometric training program with perturbation called PPT training in
31 the Weltin' study (35), in addition to their comparable testing procedure. Indeed, the
32 methodology used to assess biomechanics, the perturbed lateral reactive jump and cutting
33 maneuver conditions, and the dependent biomechanical variables were exactly the same in
34 this latter study as in the present one.
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55 Pre and post training measurements evaluated three-dimensional trunk and pelvis kinematics
56 during perturbed lateral reactive jumps, and additionally the knee joint moment during 45°
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1 cutting maneuvers. Core endurance and power as well as jump performance and agility were
2 also evaluated.
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7 **Subjects**

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10 An *a priori* power analysis was conducted to estimate the sample size based on the measured
11 improvement in the intervention group (effect size of 0.6 for trunk kinematic data) of recent
12 published research (35). It was estimated that 19 participants were needed to achieve 80%
13 statistical power with an alpha level of 0.05. This sample size is in line with other studies
14 (17). Twenty-two females were initially enrolled in the study to account for possible dropouts.
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18 All participants were interviewed individually to assess eligibility for participation. They had
19 to meet the following inclusion criteria: at least five years of active participation in team
20 sports with high exposure to running, jumping and cutting tasks, no additional core stability or
21 balance training, no history of anterior cruciate ligament injury, trunk or back injury,
22 neurological disorders or any current pain. Participants trained at least three times a week (up
23 to five times) and played at different levels (1st to 5th division). Three participants withdrew
24 from the study due to injuries (two ankle ligament injuries and one hamstring muscle tear)
25 that occurred during their regularly scheduled season practices and matches, resulting in more
26 than two missed training sessions in the present intervention. Accordingly, 19 female athletes
27 were included in the analysis (22 ± 3 years, 172 ± 7 cm, 61 ± 7 kg, 9 ± 4 years sport
28 experience).
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48 The study was approved by the local ethics committee (approval number: 390/13) and
49 conformed to the requirements stipulated in the Declaration of Helsinki. All participants were
50 informed about the procedures, purpose, benefits and possible risks associated with the
51 experimental set-up prior to signing an institutionally approved informed consent document to
52 participate in the study.
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Procedures

Intervention. All participants took part in regularly scheduled season practices and matches, in addition to attending the present core stability (CS) program three times per week for five weeks (15 sessions). The present CS training (Table 1) involved 15 training sessions. Each session lasted for 30min and was based on warm-up exercises, medicine ball throws, a cable lift task, and different variations of lateral shuffles. These specific exercises are relevant with respect to cutting maneuver biomechanics, since i) they are dynamic, ii) they target the core but also involve the whole-body, and iii) they are functional with respect to the nature of a cutting maneuver, involving trunk and pelvis segment rotations while pushing medially and upwards with the stance leg into the new movement direction. Together with a progressive increase in the intensity and the introduction of perturbation in the latter sessions, the present CS training should be more effective than previously tested programs seeking to improve cutting maneuver biomechanics (17,35,38). Participants were given instructions and illustrations about the exercises and were supervised by athletic coaches to ensure proper and effective execution of the movement techniques. Particular attention was paid to the rotation of the hip during the medicine ball throw. Indeed, hips should lead the movement followed by the upper body. The ball should be held at the hip level opposite the wall, and the foot should rotate together with the hip. Focus was set on turning the shoulders and torso, as well as combining familiar movements of upright rows and an incline press during the cable lift. During shuffles, athletes had to keep their weight forward to maintain an upright torso position with respect to the vertical axis in the frontal plane and to point their toes forwards.

The motor learning principles behind the training procedure referred mainly to the internal focus of attention and explicit learning during the first 6 training sessions. Then, an external focus of attention and implicit learning were introduced by focusing on the medicine ball

1 (“trying to launch the ball from the hip”) or performing shuffles using mirror drills with
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3 partners. Moreover, differential learning was initiated by having a variety of movement
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5 patterns targeting the trunk and pelvis segments re-orientation throughout the intervention and
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7 changing the environment (different training partners, resistances, and perturbations).
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12 Table 1 about here
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17 *Testing.* Participants performed different lateral movements and performance tests prior to CS
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19 training (PRE) and after the CS training intervention (POST). Post testing was scheduled in
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21 order to match conditions of the PRE measurements, in terms of day of the week, time of the
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23 day, and sleep.
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27 Firstly, participants performed perturbed lateral reactive jumps (LRJ) to focus on movement
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29 control during a functional task associated with high trunk lateral lean in the frontal plane.
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31 From a standing position, subjects performed a lateral reactive movement by jumping to their
32
33 left side and then pushing off with their left leg to get back to their original position. In order
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35 to induce lateral perturbations, subjects performed LRJ on a motor-driven plate, which could
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37 move in the horizontal (medio-lateral) direction. The specially designed motor-driven plate
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39 (University of Sport Science, Freiburg, Germany) was comprised of two independently
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41 moving plates (1.15 m × 0.3 m), each driven by a separate motor (AKM51G, Danaher
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43 Motion, Düsseldorf, Germany). LRJ were performed either without any perturbation (stable
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45 condition) or with a perturbation to the left (sliding condition) or to the right (counteracting
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47 condition) as soon as the foot made initial contact with the plate. Each perturbation consisted
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49 of a 10 cm translation. Unpredictability was introduced using these three different landing
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51 modalities (stable, sliding, and counteracting) that were unknown prior to movement
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53 execution. The perturbation was triggered by breaking a light beam (M18 series, Panasonic
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1 Electric Works Europe AG, Holzkirchen, Germany). Details of this material have been
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3 previously described in the literature (23).

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5 Secondly, participants were asked to perform either cutting maneuvers to 45°, crossovers to -
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7 20°, or straight runs on a force plate (BP600900, AMTI®, Watertown, USA) after
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9 approaching the force plate (FP) at $4 \pm 0.2 \text{ m}\cdot\text{s}^{-1}$. The direction of the movement was indicated
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11 in a randomized order by a light signal occurring 650 ms before the left foot contacted the FP.
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13 The visual light stimulus was triggered automatically during the approach run via a light
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15 switch (M18 series, Panasonic Electric Works Europe AG, Holzkirchen, Germany). The 45°
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17 cutting maneuver to the right was the only movement further analyzed due to its relevance
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19 when investigating performance and injury aspects of changing direction tasks. Details of
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21 these procedures have been previously described in the literature (24). The test-retest
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23 reliability of these specific biomechanical evaluations were additionally tested for nine
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25 participants providing an intraclass correlation coefficient (ICC) value for the different
26
27 dependant variables. The reliability of the trunk, pelvis, and knee kinematics during LRJ was
28
29 good, with ICC values respectively above 0.94, 0.89 and 0.87 when averaged over the three
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31 conditions. During cuttings, the reliability of the trunk and pelvis kinematics was good (ICC >
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33 0.81 and 0.85, respectively), and the ICC values for knee joint moments were 0.88 (flexion),
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35 0.72 (abduction), and 0.52 (external rotation). Based on the ICC values, the standard error of
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37 measurement (SEM) was determined to provide further valuable information in order to
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39 interpret significant effects detected during LRJ and cuttings with the present repeated
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41 measures design.
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51 Finally, core endurance and power, jump performance, and agility were evaluated. Holding
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53 times during a prone plank and a left side plank were used to evaluate core endurance. Time
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55 was stopped when participants could not hold the plank anymore. Jump performance was
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57 evaluated by broad and lateral jumps, agility with the 5-10-5 yards test and core power with a
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1 cable lift test. This latter test targets the action of the hips, torso rotators, upper back, chest
2 and shoulders while turning the trunk away from the strength machine as the hands first pull
3 the rope cable handle towards the chest and then push up and away (Figure 1).
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10 Figure 1 about here
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14 The rationale for all these tests was the importance of agility, leg muscle strength, core
15 endurance and power for high performance in team ball sports. The best out of two broad
16 jumps and two lateral jumps to the right were determined from the distance measured. The
17 time taken to accomplish the agility test was measured manually. The cable lift test was
18 conducted three times at 70% of the one-repetition maximum. The vertical acceleration signal
19 of an accelerometer (University of Sport Science, Freiburg, Germany) placed on the top of the
20 weight stack was filtered with a low pass Butterworth filter (4th order, 20 Hz cut-off
21 frequency) and then integrated to obtain velocity. Lift force was calculated based on
22 Newton's second law. Finally, core power was determined as the product of force and
23 velocity. The good reliability for lower back stabilization exercises (ICC > 0.96), as well as
24 for the 5-10-5 yards agility test (ICC > 0.87) have been reported in the literature (21,31). The
25 test-retest reliability of this specific cable lift task across the nine participants was
26 additionnally evaluated (ICC = 0.67).
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46 All participants were familiar with such movements due to their sport practice and were given
47 enough practice trials to feel comfortable with all task modalities prior to the measurements.
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54 *Data analysis.* Three-dimensional leg kinematics were recorded using reflective skin markers
55 (Ø 14 mm) placed on anatomical landmarks of the subjects' trunk (three markers), pelvis
56 (four markers), left thigh (three markers), shank (four markers), and foot (six markers). The
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1 markers were captured with a 12-camera motion analysis system (Vicon MXTM, VICON
2 Motion Systems Ltd.®, Oxford, UK) with a sampling frequency of 200 Hz. A static trial with
3 the subject standing in a pre-defined neutral position was used to define the kinematic model
4 and to calculate segment lengths and joint centers. The kinematic modeling was performed
5 using the motion analysis software (Vicon Nexus 1.6.1, VICON Motion Systems Ltd.®,
6 Oxford, UK). Joint kinematics in three rotational degrees of freedom were determined using
7 an yxz Euler rotation sequence of the respective segment coordinate system according to the
8 global reference system defined in Vicon. This rotation sequence was around the
9 flexion/extension axis first, then around the abduction/adduction axis, followed by rotation
10 around the external/internal axis. This marker placement and kinematic modeling were used
11 in previously published articles (22,36).
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27 The marker trajectories and ground reaction force signals were both filtered with a low pass
28 Butterworth filter (4th order, 15 Hz cut-off frequency) prior to calculating external joint
29 moments with a standard inverse dynamics approach. Three-dimensional kinematic data of
30 the trunk and pelvic segments were analyzed to understand the influence of CS training on
31 core control. The three-dimensional kinematics and kinetics of the knee joint were further
32 analyzed to determine the influence of CS training on knee joint stability and loading. Both
33 kinematics and kinetics were measured during cutting maneuvers, but only kinematics was
34 observed during LRJ. These variables were analyzed at the time of their peak values during
35 the first half of ground contact during LRJ to give some insight into how CS training
36 influences the range of motion of the different body segments. However, during cutting
37 maneuvers, the different variables were determined at the time of peak knee abduction
38 moment. The trunk and pelvis kinematics were defined relative to the global coordinate
39 system, i.e., deviations from the vertical axis for trunk forward and lateral leans, and for
40 pelvis forward and medial tilts, and from the anterior-posterior axis for trunk and pelvis right
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1 axial rotation. These parameters were positive for an orientation in the new movement
2 direction (i.e., a medial lean and rotation in the right direction). Knee rotation parameters
3 were positive for an external rotation.
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10 **Statistical Analyses**

11 The selected parameters were averaged across eight trials for the different LRJ modalities and
12 the 45° cutting maneuver, whereas time for the 5-10-5 yards test was reported and the highest
13 CMJ and mean peak power value over three cable lift trials were calculated. These parameters
14 served as the basis for the statistical analysis (Statistica 12, StatSoft, Inc.®, Tulsa, OK, US).
15 All results are presented as group mean \pm standard deviation (SD). After having confirmed
16 that the data followed a normal distribution (Shapiro-Wilk W), sphericity was verified by
17 means of a Mauchly's test. The influence of CS training on dependent variables for LRJ
18 modalities was calculated using a two-way analysis of variance (General Linear Model) with
19 repeated measures to test for the main effects of and interactions between CS training (PRE
20 vs. POST) and LRJ modality (stable vs. sliding vs. counteracting). If a statistically significant
21 LRJ modality main effect was observed, Bonferroni corrected paired comparisons determined
22 where the differences occurred. The influence of CS training (PRE vs. POST) on the
23 dependent variables for the cutting maneuver and performance tasks was analyzed using
24 paired two-tailed t-tests. The magnitude of the changes was assessed with effect size (ES) and
25 a 95% confidence interval (CI). The ES was evaluated by means of Cohen's d values for
26 repeated measures designs. The ES was considered trivial (0-0.19), small (0.20-0.49), medium
27 (0.50-0.79), or large (>0.80) according to Cohen (5). The level of significance was set at $p <$
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58 **RESULTS**

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1 There was a significant main effect of CS training on trunk lateral lean ($p = 0.04$), trunk
2 axial rotation ($p = 0.002$), pelvis medial tilt ($p = 0.002$), and pelvis axial rotation ($p < 0.001$)
3 during LRJ, but no significant influence at the knee joint level (Table 2). SEM values for
4 trunk lateral lean and rotation were 0.7° and 1.4° , respectively, while the pelvis medial tilt and
5 rotation had SEM values of 1.3° and 1.7° , respectively.
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42 Statistical analysis revealed a significant main effect of the LRJ modality on trunk forward
43 lean and trunk lateral lean (both $p < 0.001$), pelvis medial tilt ($p < 0.001$), knee flexion,
44 abduction, and rotation ($p < 0.001$, $p = 0.04$ and $p < 0.001$, respectively). Significant
45 interaction effects (CS training \times LRJ modality) were found only for trunk axial rotation ($p =$
46 0.01) and knee joint abduction ($p = 0.03$). Specifically, pairwise comparisons revealed that
47 stable, sliding, and counteracting modalities yielded significantly different values from each
48 other for trunk forward lean ($p < 0.007$ for all), trunk lateral lean ($p < 0.001$ for all), pelvis
49 medial tilt ($p < 0.002$ for all), knee flexion ($p < 0.001$ for all), knee abduction ($p < 0.05$ for
50 all), and knee rotation ($p < 0.001$ for all).
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66 During the cutting maneuver (Table 3), trunk forward lean and axial rotation were not
67 influenced after CS training, whereas trunk lateral lean was significantly increased ($p = 0.03$).
68 Pelvis kinematics was not significantly influenced by CS training. Knee joint flexion moment
69 decreased significantly ($p = 0.01$) after CS training, whereas the knee joint rotation moment
70 increased ($p = 0.02$). However, the knee joint abduction moment remained at the same level
71 after CS training. SEM values were 1.6° for trunk lateral lean, and 0.28 Nm.kg^{-1} and 0.08
72 Nm.kg^{-1} for knee joint flexion and rotation moments, respectively.
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7 All core endurance (prone and side planks), jump performance, agility, and core power
8 parameters were significantly improved after CS training (Table 4).
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18 19 20 **DISCUSSION** 21

22 The main findings of the study were as follows: 1) CS training increased trunk and pelvis
23 rotation in the new movement direction during lateral reactive jumps; 2) lateral trunk lean was
24 increased during lateral movements after CS training; 3) the knee joint abduction moment was
25 not influenced by CS training; and 4) CS training improved core endurance and power, jump
26 performance, and agility.
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34 Perturbed lateral reactive jumps yielded significantly different segment and joint
35 configurations. This influence of LRJ modality has already been described in the literature
36 (24,34). Moreover, during perturbed lateral reactive jumps, the trunk and pelvis positioning
37 were influenced by CS training. Indeed, trunk lateral flexion and pelvis lateral tilt were
38 significantly increased after CS training, and both right axial rotations of these segments were
39 enhanced after training. Five weeks of dynamic and functional core stability training resulted
40 in a better positioning of the core segments in the transversal plane with increased rotation
41 towards the new movement direction during lateral reactive jumps, which is in agreement
42 with results found by Weltin et al. (35) after a training program combining plyometric
43 exercises with perturbation compared to plyometric training alone. However, core segments
44 were significantly less orientated towards the new movement direction in the frontal plane.
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1 Although significant, these changes in trunk lateral flexion and pelvis lateral tilt were rather
2 small given the standard error of the measurements (0.7° and 1.3° , respectively). During
3 unanticipated cutting maneuvers, the better orientation of trunk and pelvis segments in the
4 transversal plane seen during LRJ was lacking, which differs from the results of Weltin et al.
5 (35). In the frontal plane, pelvis medial tilt was kept at the same level and only a small 2°
6 increase in trunk lateral flexion (with respect to 1.6° SEM) was observed after CS training.
7 Core stability improvements during lateral movements after dynamic and functional core
8 stability training were limited and, therefore, our first hypothesis was mainly rejected.
9 Although the better trunk and pelvis orientation towards the new movement direction seen in
10 the transversal plane during LRJ might possibly reflect a reduced knee injury risk (6,8,10,11),
11 this was lacking during unanticipated cutting maneuvers. The increased trunk lateral lean
12 during lateral movements after CS training could be seen as a negative effect on knee joint
13 loads (8,18,36). However, in the absence of an increased knee joint abduction angle and
14 moment, this could also reflect a strategy to move the center of mass towards the new
15 direction during the stance phase (27). Nevertheless, training programs seeking to reduce
16 trunk lateral lean during cutting maneuvers should instead focus on a specific technique
17 training that is more effective (7). However, the present dynamic and functional CS training
18 influenced core stability during lateral movements to a larger extent than previous SC
19 programs (17,38).

20 Despite some core stability alterations after CS training, the knee joint abduction moment
21 was kept at the same level during unanticipated cutting maneuvers. This is in line with
22 previous studies (17,35,38) and confirms our second hypothesis. However, other
23 consequences at the knee joint level were found during unanticipated cutting maneuvers with
24 a lower knee flexion moment and higher knee external rotation moment. Although significant,
25 the increased knee external rotation moment (0.01 to 0.08 Nm.kg⁻¹) was small given its
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1 standard error of measurement and compared to the larger influence on knee joint flexion (a
2 reduction from 0.73 to 0.26 Nm.kg⁻¹), which would probably mean an overall knee joint load
3 reduction after CS training. During lateral reactive jumps, knee joint stability remained at the
4 same level after CS training.
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10 The present dynamic and functional CS training influenced all tested performance
11 parameters as hypothesized. The significant enhanced core muscle endurance and power are
12 in line with the literature (17,29,33). Jump performance and agility were also increased by
13 training. Therefore the present CS exercises can be implemented by athletes in their regular
14 training to improve performance and underlines the importance of implementing dynamic
15 movements, added resistance and functional exercises during training, as described by Hibbs
16 et al. (15).
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27 This study has some limitations that need to be considered. First, the lack of any control
28 group might reduce the impact of the results found for the intervention group. However, the
29 training was designed according to evidence from the literature based on a model for potential
30 performance benefits (15) and a framework for ACL injury prevention (9). Moreover, the
31 testing procedure used in the present study was comparable to another training study with two
32 different interventions (35), which helped with the interpretation of the present findings. The
33 sprint time during the agility test was measured manually, which might decrease accuracy of
34 the measurement. However, according to the substantial improvement of all other
35 performance parameters, we are confident of our conclusion about the enhanced athletic
36 performance after core stability training. Finally, the motor learning principles behind the
37 training procedure referred mainly to an internal focus of attention and explicit learning.
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1 self-controlled learning in order to optimize the training intervention and therefore improve
2 participants' functional performance (40).
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5 In conclusion, a 5-week dynamic and functional core stability training program improves
6 core muscles endurance and power improvement, as well as increasing jump performance and
7 agility. This might explain the better orientation of the trunk and pelvis towards the new
8 movement direction during lateral reactive jumps, especially in the transversal plane.
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10 However, this improved core stability was not observed during a more challenging and
11 dynamic task, i.e., unanticipated cuttings, during which knee joint abduction remained at the
12 same level after the training.
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24 **PRACTICAL APPLICATIONS**

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27 The practical application of this research will allow strength and conditioning professionals to
28 setup training programs with relevant exercises targeting the enhancement of core stability.
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30 By using different variations of lateral shuffles, medicine ball throws, or cable lift tasks, as
31 described in the present study, it is possible to increase core endurance and power, as well as
32 jump performance and agility of trained individuals. These exercises can be performed in
33 every gym with very simple sport equipment. Ultimately, these improvements are likely to
34 enable athletes to perform at a better level with a reduced risk of knee joint injury.
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46 **ACKNOWLEDGMENTS**

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49
50 The authors report no conflict of interest and state that the results of the present study do not
51 constitute endorsement of the product by the authors or the NSCA.
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Figure

Figure 1 Schematic view of the cable lift test.

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Tables

Table 1 Overview of the dynamic and functional core stability program.

* 30sec break between sets and 2min30sec between exercises.

** warm-up based on forward lunge, lateral lunge, backward lunge with a twist, drop lunge, hand walk, hip crossover and scorpion exercises.

*** resistance was induced by elastic ropes (three degrees of resistance were generated).

Table 2 Mean \pm SD values of the different kinematic variables averaged over all three lateral reactive jumps (LRJ) modalities (pooled) performed before (PRE) and after (POST) the core stability training intervention.

The influence of the core stability training intervention is reported using p , 95% confidence interval (95%CI) and effect size (ES).

*, **, *** indicates significant differences between PRE and POST with $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively.

Table 3 Mean \pm SD values of the different kinematic and joint moment variables during cutting maneuvers performed before (PRE) and after (POST) the core stability training intervention.

The influence of the core stability training intervention is reported using p , 95% confidence interval (95%CI) and effect size (ES).

, * indicates significant differences between PRE and POST with $p < 0.01$ and $p < 0.001$, respectively.

Table 4 Mean \pm SD values of the different core endurance and athletic performance variables before (PRE) and after (POST) the core ctability training intervention.

The influence of the core stability training intervention is reported using p , 95% confidence interval (95%CI) and effect size (ES).

*, **, *** indicates significant differences between PRE and POST with $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively.

Figure 1

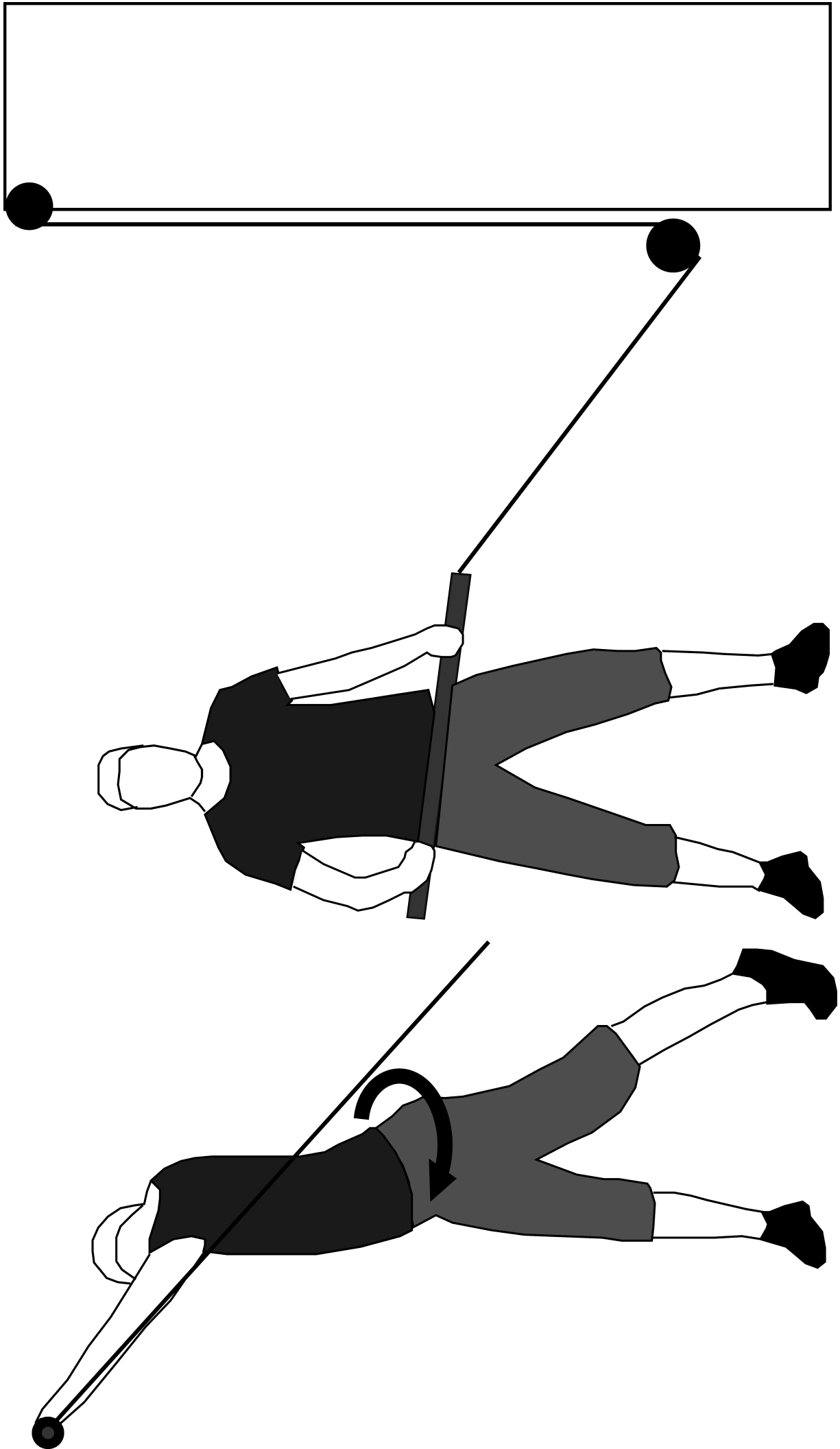


Table 1

CS training sessions	Exercises*
1 - 3	<p>Warm-up (5min)**</p> <p>Medicine ball throw : right technique learning with a 2kg ball (5min)</p> <p>Medicine ball throw (2kg ball): 3 x 10 on each side (5min)</p> <p>Cable lift: right technique learning with the first degree of resistance (5min)***</p>
4 - 6	<p>Warm-up (5min)</p> <p>Medicine ball throw (2kg ball): 3 x 10 on each side (5min)</p> <p>Cable lift (first degree of resistance): 3 x 10 on each side (5min)</p> <p>Lateral shuffle: right technique learning (5min)</p>
7 - 9	<p>Warm-up (5min)</p> <p>Medicine ball throw (3kg ball): 3 x 10 on each side (5min)</p> <p>Cable lift (second degree of resistance): 3 x 10 on each side (5min)</p> <p>Lateral shuffle: mirror drills with partner (5min)</p>
10 - 12	<p>Warm-up (5min)</p> <p>Medicine ball throw (3kg ball): 3 x 10 on each side (5min)</p> <p>Cable lift (third degree of resistance): 3 x 10 on each side (5min)</p> <p>Lateral shuffle: shuffles with increased resistance through elastic ropes attached to the pelvis (5min)</p>
13 - 15	<p>Warm-up (5min)</p> <p>Cable lift (third degree of resistance): 3 x 10 on each side (5min)</p> <p>Lateral shuffle: shuffles with increased resistance through elastic ropes attached to the pelvis (5min)</p> <p>Lateral shuffle: shuffles with perturbation through elastic ropes more or less released by the athletic coach (5min)</p>

Table 2

Variable	PRE (pooled LRJ)	POST (pooled LRJ)	<i>p</i> value	95% CI	ES
Trunk Forward Lean (°)	27.2 ± 5.1	29.1 ± 5.0	0.06	[-3.9, 0.1]	0.47
Trunk Lateral Lean (°)	-5.6 ± 4.7	-7.0 ± 5.0*	0.04	[0.1, 2.9]	0.50
Trunk Axial Rotation (°)	2.3 ± 9.1	6.3 ± 10.2**	0.002	[-5.2, -1.5]	1.1
Pelvis Forward Tilt (°)	17.7 ± 6.4	18.4 ± 4.6	0.35	[-4.7, 0.5]	0.27
Pelvis Medial Tilt (°)	-5.6 ± 4.9	-7.6 ± 4.2**	0.002	[0.9, 3.2]	0.77
Pelvis Axial Rotation (°)	4.9 ± 8.9	8.6 ± 7.4****	<0.001	[-5.4, -2.2]	1.0
Knee Flexion (°)	58.8 ± 5.6	57.6 ± 6.6	0.06	[-0.1, 2.5]	0.54
Knee Abduction (°)	7.1 ± 5.2	8.3 ± 3.8	0.25	[-3.5, 1.0]	0.23
Knee Ext. Rotation (°)	-10.4 ± 7.1	-10.3 ± 5.2	0.97	[-2.6, 2.5]	0.02

Table 3

Variable	PRE	POST	<i>p</i> value	95% CI	ES
Trunk Forward Lean (°)	7.5 ± 5.2	6.0 ± 5.7	0.28	[-1.4, 4.4]	0.26
Trunk Lateral Lean (°)	-3.8 ± 3.9	-5.8 ± 4.4*	0.03	[0.3, 3.3]	0.70
Trunk Axial Rotation (°)	-9.0 ± 8.6	-8.1 ± 7.7	0.59	[-4.6, 2.7]	0.11
Pelvis Forward Tilt (°)	17.5 ± 5.7	17.6 ± 4.6	0.90	[-1.5, 1.2]	0.03
Pelvis Medial Tilt (°)	13.0 ± 4.7	11.8 ± 3.8	0.29	[-1.1, 3.5]	0.23
Pelvis Axial Rotation (°)	7.7 ± 6.9	9.9 ± 7.3	0.15	[-5.3, 0.9]	0.35
Knee Flexion Moment (Nm.kg ⁻¹)	0.73 ± 0.71	0.26 ± 0.80**	0.01	[0.11, 0.81]	0.69
Knee Abduction Moment (Nm.kg ⁻¹)	0.74 ± 0.45	0.71 ± 0.48	0.88	[-0.27, 0.31]	0.05
Knee Ext. Rotation Moment (Nm.kg ⁻¹)	0.01 ± 0.10	0.08 ± 0.12*	0.02	[-0.13, -0.02]	0.64

Table 4

Variable	PRE	POST	<i>P</i> value	95% CI	ES
Prone Plank (s)	79.0 ± 22.1	93.3 ± 26.7**	0.006	[-23.9, -4.8]	0.81
Side Plank (s)	51.3 ± 17.2	69.9 ± 19.4***	<0.001	[-25.5, -11.6]	1.4
Broad Jump (m)	1.78 ± 0.19	1.86 ± 0.18***	<0.001	[-12.6, -4.8]	0.99
Side Jump (m)	1.71 ± 0.16	1.78 ± 0.13**	0.002	[-10.8, -2.7]	0.80
Agility (s)	5.4 ± 0.3	5.2 ± 0.3***	<0.001	[0.1, 0.3]	0.98
Core Power (W)	265 ± 56	300 ± 43***	<0.001	[-49, -19]	1.2