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Neuromuscular and athletic performance following core strength training in elite youth soccer: Role of instability

O. Prieske[1], T. Muehlbauer[1], R. Borde[1], M. Gube[2], S. Bruhn[2], D. G. Behm[3], U. Granacher[1]

[1]Division of Training and Movement Sciences, Research Focus Cognition Sciences, University of Potsdam, Potsdam, Germany, [2]Department of Sports Science, University of Rostock, Rostock, Germany, [3]School of Human Kinetics and Recreation, Memorial University of Newfoundland, St. John's, Newfoundland, Canada
Corresponding author: O. Prieske, DipSpSc, Division of Training and Movement Sciences, Research Focus Cognition Sciences, University of Potsdam, Am Neuen Palais 10, House 12, 14469 Potsdam, Germany. Tel: +49 331 977 1121, Fax: +49 331 977 4022, E-mail: olaf.prieske@uni-potsdam.de

Cross-sectional studies revealed that inclusion of unstable elements in core-strengthening exercises produced increases in trunk muscle activity and thus potential extra stimuli to induce more pronounced performance enhancements in youth athletes. Thus, the purpose of the study was to investigate changes in neuromuscular and athletic performance following core strength training performed on unstable (CSTU) compared with stable surfaces (CSTS) in youth soccer players. Thirty-nine male elite soccer players (age: 17 ± 1 years) were assigned to two groups performing a progressive core strength-training program for 9 weeks (2–3 times/week) in addition to regular in-season soccer training. CSTS group conducted core exercises on stable (i.e.,

floor, bench) and CSTU group on unstable (e.g., Thera-Band® Stability Trainer, Togu© Swiss ball) surfaces. Measurements included tests for assessing trunk muscle strength/activation, countermovement jump height, sprint time, agility time, and kicking performance. Statistical analysis revealed significant main effects of test (pre vs post) for trunk extensor strength (5%, $P < 0.05$, $d = 0.86$), 10–20-m sprint time (3%, $P < 0.05$, $d = 2.56$), and kicking performance (1%, $P < 0.01$, $d = 1.28$). No significant Group × test interactions were observed for any variable. In conclusion, trunk muscle strength, sprint, and kicking performance improved following CSTU and CSTS when conducted in combination with regular soccer training.

Competitive soccer can be characterized as an intermittent sport with high demands on several physical components. More specifically, outfield players (e.g., wing-back, central midfield, striker) require high levels of aerobic capacity, speed, agility, and maximal as well as explosive strength (Stølen et al., 2005). For instance, Stølen et al. (2005) reported that a sprint bout occurs approximately every 90 s during a top-level soccer game, each lasting on average for 2–4 s. In addition, it has been shown that elite youth and adult athletes are superior to sub-elite or recreational soccer players regarding performance measures such as muscular strength and sprint time (Cometti et al., 2001; Gissis et al., 2006). Thus, it can be argued that athletic performance is crucial in competitive (youth) soccer, particularly in elite athletes.

It is well known that athletic performance in soccer players can be improved by means of strength training (Ronnestad et al., 2008). In terms of youth strength training, substantial research has been conducted regarding feasibility, safety, and effectiveness (Lloyd et al., 2014). In fact, there is evidence that strength training has the potential to induce strength gains and to improve sport-

specific performances in youth soccer players (Wong et al., 2010). More recently, the importance of trunk muscle strength and trunk stability has been described for performance enhancements in sport-specific activities (Kibler et al., 2006). This assumption was reinforced by cross-sectional studies showing significant associations between variables of trunk muscle strength and short-distance sprint, agility, and jump performance (Nesser et al., 2008; Sharma et al., 2012; Prieske et al., 2014a). Moreover, Hoshikawa et al. (2013) reported significant improvements in unilateral hip muscle strength and jump performance in adolescent soccer players following the combination of core stability/strength training and regular soccer training as compared with single soccer training. With reference to these findings, it seems plausible to argue that core strengthening may have the potential to improve athletic performance in youth soccer athletes.

Notably, performance in several sports such as soccer often occurs on relatively unstable surfaces (e.g., jumping and landing on uneven natural turf, kicking a ball while being impeded by an opponent). Thus, according to the concept of training specificity (Behm & Sale,

1993), it was postulated that training must attempt to closely mimic the demands of the respective sport-specific activity (Behm et al., 2010b). When using the same absolute load (e.g., body weight) during core-strengthening exercises, trunk muscle activity increased under unstable [e.g., Swiss ball, BOSU (i.e., both sides up) ball] as compared with stable surface conditions (Vera-Garcia et al., 2000). Thus, the integration of unstable elements in core strength training could provide an extra stimulus for strength promotion in soccer players resulting in superior performance enhancements compared with core strength training under stable conditions. To the best of our knowledge, there is only one study available that investigated the impact of core strengthening on stable vs unstable surfaces in healthy but untrained children (Granacher et al., 2014). Following 6 weeks of training (2 sessions/week), significant performance improvements were observed for trunk muscle strength, stand-and-reach test, jumping sideways test, and Y balance test. Translating these findings to trained youth athletes appears to be disputable, given that the adaptive reserve is lower for physical factors (e.g., maximal strength; Rhea et al., 2003) and higher for coordinative factors (e.g., perception; Yarrow et al., 2009) in trained compared with untrained subjects. More precisely, the study of Rhea et al. (2003) revealed that maximal training-related strength gains are lower in athletes as compared with untrained individuals. Conversely, athletes appear to be superior to novices in terms of coordinative adaptations because of enhanced performance at the level of perception, anticipation, and decision making (Yarrow et al., 2009).

Therefore, the aim of this study was to investigate performance changes following core strength training performed on stable (CSTS) vs unstable surfaces (CSTU) when conducted in combination with regular soccer training on trunk muscle strength/activation and proxies of athletic performance in elite youth soccer players. Based on selected results reported in the literature (Vera-Garcia et al., 2000; Kibler et al., 2006; Nesser et al., 2008; Behm et al., 2010b; Sharma et al., 2012; Behm & Colado-Sanchez, 2013; Hoshikawa et al., 2013), we hypothesized that soccer players in the CSTU group as compared with the CSTS group show larger improvements in trunk muscle strength/activation and measures of athletic performance (i.e., strength, speed, agility, kicking performance) following core strength training in combination with regular soccer training.

Methods
Participants

With reference to the study of Granacher et al. (2014), an *a priori* power analysis (Faul et al., 2007) with an assumed Type I error of 0.05 and a type II error rate of 0.20 (80% statistical power) was conducted for results in the standing long jump test as a proxy of athletic performance and revealed that 34 persons would be sufficient to observe a medium group × test interaction effect. Because

Table 1. Characteristics of study participants by group

Characteristic	CSTS ($n = 20$)	CSTU ($n = 19$)
Age (years)	16.6 ± 1.1	16.6 ± 1.0
Body height (m)	1.82 ± 0.05	1.79 ± 0.07
Body mass (kg)	72.5 ± 6.3	69.4 ± 7.2
Body mass index (kg/m²)	22.0 ± 1.2	21.6 ± 1.2
Team (U17/U19)	9/11	9/10
Leg preference (right/left)	16/4	15/4

Note: Values are mean and standard deviation.
CSTS, core strength training performed on stable surface; CSTU, core strength training performed on unstable surface.

of potential dropouts, 39 male elite youth soccer players agreed to participate in the study after experimental procedures were explained. Participants were randomly assigned to one of two intervention groups (i.e., CSTS or CSTU) using the method of randomly permuted blocks (stratified randomization) on a publicly accessible website (http://www.randomization.com). No significant baseline differences were found between groups in terms of age, body mass, body height, and body mass index (Table 1). The integration of a passive control group with a similar training status was impossible because it is not feasible to prevent elite athletes from training for 9 weeks. Further, previous studies using nonelite or sub-elite instead of elite subjects, clearly indicated the effectiveness of core strength training when compared with no or regular training only (Sharma et al., 2012; Hoshikawa et al., 2013). Participants have occasionally performed core-strengthening exercises prior to entering the study (e.g., during rehabilitation of prior injuries) but none of them suffered from acute musculoskeletal, neurological, or orthopedic disorders that might have affected their ability to execute core strength training and athletic performance tests. Parents' written informed consent and minors' assent were obtained before the start of the study. Next to physical education classes, participants were engaged in supervised competitive soccer training on a regular basis for six training sessions per week each lasting approximately 90 min and one match at the weekend. Local ethical permission was given, and all experiments were conducted according to the declaration of Helsinki.

Experimental procedure

To test our hypothesis, adaptations following CSTS vs CSTU in combination with regular soccer training were investigated using a parallel group randomized trial design. Training periods lasted 9 weeks to enable neuromuscular adaptive processes (Behm, 1995). Training-related changes were verified by analyzing measures of trunk muscle strength, jump, sprint, agility, and kicking performance. Additionally, trunk muscle activity was assessed in a subsample of the study participants. In order to keep the effects of neuromuscular fatigue minimal, pre- and posttests were conducted in the training facilities of the soccer team on three separate days within 1 week. The tests were performed in the same sequence for each player during pre- and posttesting. Before testing, all participants underwent a standardized warm-up procedure. Prior to sprint, agility, and kicking performance tests, the warm-up consisted of submaximal running (5 min), 2–3 submaximal short-distance sprints (e.g., 10–15 m) and soccer-specific technical drills (e.g., skipping, short dribbling, pass game). Prior to strength and muscle activity measurements, submaximal lower limb exercises [e.g., 10 squats, 3–5 countermovement jumps (CMJ)] were performed.

Core strength-training programs

Both training groups participated in a 9-week in-season core strength-training program. In addition to the regular soccer
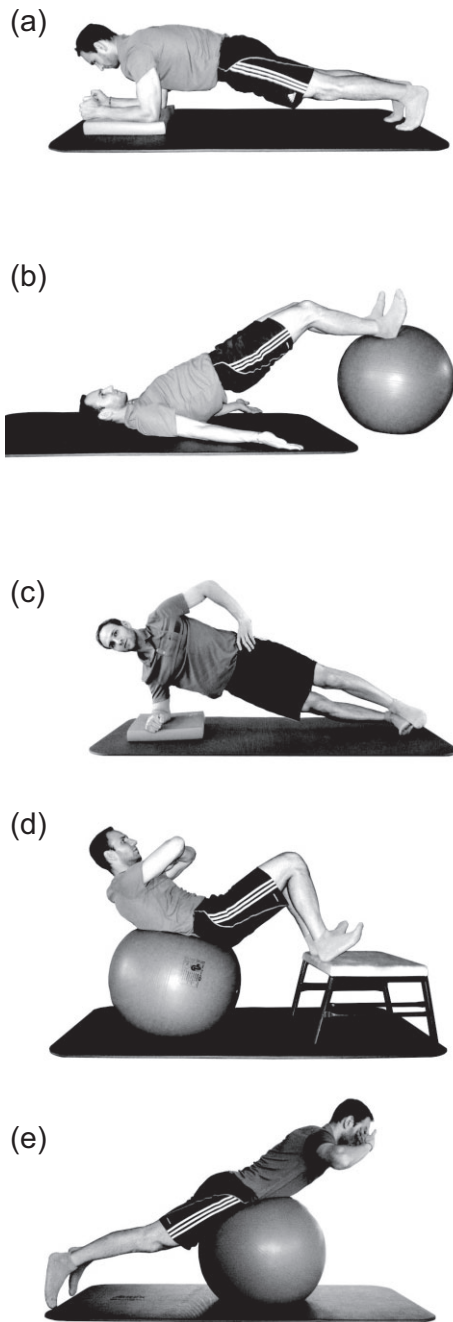
Fig. 1. Core strength-training exercises of the first phase of training performed under unstable conditions: prone plank (a), shoulder bridge (b), side bridge (c), crunch (d), and back extension (e).

strength-training program (Akuthota et al., 2008). While participants of the CSTS group performed all core-strengthening exercises under stable conditions (i.e., floor, bench), subjects in the CSTU group executed the same exercises on highly unstable surfaces that are frequently used during athletic training and rehabilitation (e.g., Airex® Balance Pad, Airex AG, Sins, Switzerland; Thera-band® Stability Trainer, Ludwig Artzt GmbH, Dornburg, Germany; Togu® Swiss ball, TOGU GmbH, Prien-Bachham, Germany). During the 9-week training period, training intensity was progressively increased for each exercise in a graded four-phase mode (each 2–3 weeks in duration). Progression was ensured by modulating lever length, muscle action (i.e., isometric vs dynamic), additional load (e.g., weight plates), and the level of instability (i.e., reduction of base of support, additional opposite limb movements; Table 2). Subjects' adherence rates were recorded throughout the study period.

Assessment of trunk muscle strength and activity

According to the study of Tarnanen et al. (2008), maximal isometric force (MIF) of the trunk extensors and flexors was measured in a standing position with the feet side by side and 20 cm apart. Test protocols assessing isometric trunk muscle strength in a standing position have proved to be reliable [intraclass correlation coefficient (ICC) > 0.91] (Hutten & Hermens, 1997). During maximal isometric trunk flexion and extension, subjects were firmly fixed in the testing position using straps to keep the lower body stable. The trunk flexors were tested with the back touching the back rest [i.e., trunk flexion, Fig. 2(a)], the trunk extensors were tested when facing the wall (Fig. 2(b)). The harness was attached to a piezo-electric force transducer (type 9311B; Kistler®, Winterthur, Switzerland) with a metal lock and the force transducer was attached to the measurement frame. The harness-force transducer assembly was adjusted in order to ensure an upright standing position. Maximal isometric trunk flexion and extension actions were conducted in a randomized order. All participants performed 3–4 maximal isometric actions lasting 3 s in each movement direction. For each trial, participants were thoroughly encouraged to act "as forcefully and as fast as possible." Proper care was taken to assure that participants kept their legs straight and their heels on the floor. Trials with an identified initial countermovement were discarded (by visual inspection of the force time curve). The force signal was amplified using a charge amplifier (type 5011B; Kistler®), analog-to-digital converted (TeleMyo 2400R G2 Analog Output Receiver, Noraxon®, Scottsdale, Arizona, USA), sampled at 1500 Hz, and finally stored on a computer running MyoResearch XP Master Edition software (version 1.08.17, Noraxon®). MIF was defined as the maximal value of the force time curve. The trial with the highest MIF value was used for further analysis.

During MIF trials, electromyographic (EMG) activity of m. rectus abdominis and m. erector spinae lumbalis was measured using circular bipolar surface electrodes (Ambu®, type Blue Sensor P-00-S/50, Ag/AgCl, diameter: 13 mm, center-to-center distance: 25 mm, Ballerup, Denmark) in a subsample of the participants (CSTS: $n = 6$, CSTU: $n = 7$). The trunk muscles were analyzed on the dominant side in terms of leg preference (Coren, 1993). Electrodes were positioned on the muscle bellies according to the European recommendations for surface electromyography (Fig. 3; Hermens et al. 1999). The longitudinal axes of the electrodes were in line with the direction of the underlying muscle fibers. Inter-electrode impedance was kept below 5 kΩ by means of shaving, slightly roughening, degreasing, and disinfecting the skin. The location of the electrodes was marked with permanent ink for identical position on pre- and posttesting. The EMG signals were amplified and recorded telemetrically (TeleMyo 2400 G2, Noraxon®) at a sampling frequency of 1500 Hz. Synchronization of force and EMG data was achieved by analog-to-digital conversion on the same I/O board. For later offline analysis, heart muscle

practice, the intervention program had to be carried out 2–3 times a week supervised by an experienced team physiotherapist. All participants conducted a ∼ 30-min core strength-training regime comprising multiple sets (i.e., 2–3 sets) of the same five core-strengthening exercises for frontal [i.e., prone planks (Fig. 1(a)), crunches (Fig. 1(d))], dorsal [i.e., shoulder bridges (Fig. 1(b)), back extensions (Fig. 1(e))], and lateral trunk muscles [i.e., side brides (Fig. 1(c))] with 15–20 s contraction time (isometric condition) or 15–20 repetitions (dynamic condition). This conditioning program complies with an example for an evidence-based core

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Table 2. Progression during 9 weeks of core strength training

Phase	Week	Exercises and used unstable surface*
1	1–2	• Static prone plank with forearms on Airex® Balance Pad • Static shoulder bridge with heels on Togu© Power Ball • Dynamic side bridge with forearm on Airex® Balance Pad • Crunches with lower back on Togu© Power Ball and feet on a bench • Dynamic back extensions with pelvis and ribs on Togu© Power Ball and feet fixed at the wall
2	3–5	• Static single arm plank with forearm on Airex® Balance Pad and one arm reached out parallel to the floor • Static shoulder bridge with vertical arm reach and heels on Togu© Power Ball • Dynamic side bridge with forearm on Airex® Balance Pad and 1 arm reached out vertically • Loaded crunches with added weight plate, lower back on Togu© Power Ball and feet on a bench • Loaded dynamic back extensions with added weight plate, pelvis, and ribs on Togu© Power Ball and feet fixed at the wall
3	6–7	• Static body saw with forearm on Thera-Band® Stability Trainer and contralateral arm and ipsilateral leg reached out parallel to the floor • Static single leg shoulder bridge with heel on Togu© Power Ball and one leg reached out • Dynamic side bridge with forearm on Thera-Band® Stability Trainer and lower leg lifted • Loaded crunches with soccer ball in hands reached out over head, lower back on Togu© Power Ball and feet on a bench • Loaded dynamic back extensions with soccer ball in hands reached out over head, pelvis and ribs on Togu© Power Ball and feet fixed at the wall
4	8–9	• Dynamic body saw with forearm on Thera-Band® Stability Trainer and contralateral arm and ipsilateral leg swinging parallel to the floor • Static single leg shoulder bridge with heel on Togu© Power Ball and ipsilateral arm and contralateral leg reached out • Dynamic side bridge with forearm on Thera-Band® Stability Trainer, with vertical arm reach and lower leg lifted • Loaded crunches with soccer ball in hands reached out over head, lower back on Togu© Power Ball and 1 feet on a bench • Loaded dynamic back extensions with soccer ball in hands reached out over head, pelvis, and ribs on Togu© Power Ball and one foot fixed at the wall

*This exercise sequence was only conducted by the core instability strength training group, whereas participants of the core stability strength training group performed the same exercises on stable surfaces (i.e., floor, bench).
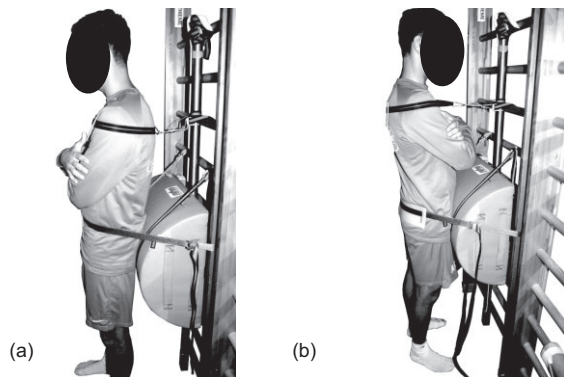

(a)   (b)

Fig. 2. Measurement of maximal isometric force of the trunk flexors (a) and trunk extensors (b).
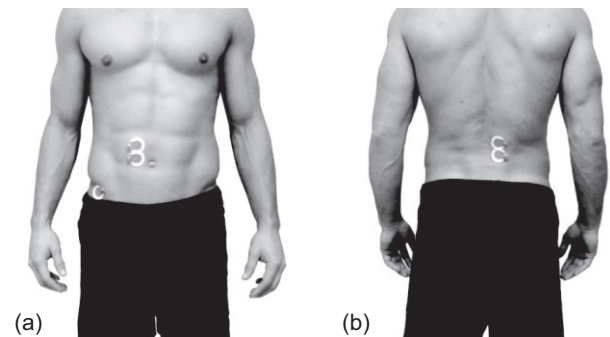

(a)   (b)

Fig. 3. Electrode placement for the assessment of muscle activity of m. rectus abdominis (a) and m. erector spinae lumbalis (b). A reference electrode was placed on anterior superior iliac spine (a).

electrical activity artifacts were removed from the trunk muscle signals (Prieske et al., 2013). Subsequently, EMG signals were digitally high-pass filtered (second-order Butterworth, 5 Hz cut-off frequency) followed by a moving root mean square filter with a time constant of 50 ms (Prieske et al., 2014b). Mean average voltage (MAV; defined as integrated EMG normalized to integration time) was calculated for the time intervals 100 ms pre- and post-MIF and normalized to peak EMG (Prieske et al., 2014b).

Assessment of athletic performance

CMJ test

To assess lower limb muscle power, participants performed maximal vertical CMJ on a three-dimensional force plate (type 9286AA; Kistler®). Excellent test-retest reliability has been reported for the CMJ test with an ICC value of 0.98 (Markovic

et al., 2004). The vertical ground reaction force was sampled at 1000 Hz. While standing on a force plate in an upright position, subjects were instructed to begin the jump with a downward movement, which was immediately followed by a concentric upward movement, resulting in a maximal vertical jump. During jumping, hands were held akimbo and the depth of the downward movement was freely chosen to allow a natural movement. Three CMJ trials with a resting period of 1 min between jumps were conducted. The best CMJ trial in terms of maximal jump height was taken for further data analysis. Jump height was calculated according to the following formula: jump height $= 1/8 \times g \times t^2$, where g is the acceleration due to gravity and t is the flight time (Prieske et al., 2013).

20-m linear sprint test

The performance of a 20-m linear sprint was measured using three double-light barriers (WITTY; Microgate Srl, Bolzano, Italy;

accuracy of 0.001 s). Sprint intervals of 10 m and 20 m were analyzed. Excellent test-retest reliability has been reported for 10- and 20-m time in 20-m sprint test with ICCs ranging from 0.91 to 0.93 (Moir et al., 2004). The subjects began the test with one foot on the starting line in frontal erect position and time measurement started when subjects passed the first photoelectric cells. We did not provide a starting signal so that the subjects were able to individually start the test. Thus, reaction time did not influence our findings. Participants were instructed to start from the starting line and to run as fast as possible over the 20-m distance. Each participant had three trials with a 5-min rest between single trials. The trial with the best 20-m linear sprint time (least time) was used for further analysis. Finally, sprint times for different intervals (i.e., 0–10 m, 10–20 m, 0–20 m) were calculated from the best trial.

T agility test

Agility was assessed by means of the T agility test. Previously, this test proved to be valid ($0.42 \leq r \leq 0.73$) and reliable (ICC = 0.98) for the assessment of change of direction performance as well as lower-extremity speed and power in young healthy athletes (Pauole et al., 2000). For this purpose, a figure-T course was created using four cones. Subjects were instructed to run and shuffle as fast as possible passing each cone (Fig. 4). Thus, subjects had to continuously change direction throughout the testing procedure. Similar to the 20-m linear sprint test, we did not provide a starting signal so that the subjects were able to individually start the test. Three test trials were performed, and times were recorded to the nearest 0.001 s using one double-light barrier of the WITTY system. The rest between trials was 5 min. The best (least time) out of three test trials was used for analysis.

Kicking performance test

Kicking performance (i.e., maximal ball velocity) was determined during a penalty kick (i.e., ball-goal distance: 11 m) with a standard soccer ball (i.e., FIFA standard size 5) using a Doppler radar gun (Stalker Sport 2, Applied Concepts, Inc./Stalker Radar, Plano, Texas, USA). In terms of maximal ball velocity, test-retest reliability has been shown to be excellent (i.e., $0.87 \leq \text{ICC} \leq 0.93$) in youth soccer players (Bacvarevic et al., 2012). The participants were asked to perform three penalty kicks with their dominant leg
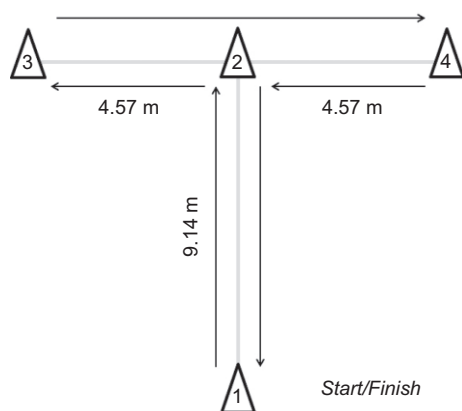
Fig. 4. T agility test. Starting from cone 1, subjects were instructed to run as fast as possible to the second cone, shuffle to the left (cone 3), then shuffle to the right to cone 4, shuffle again to the left (cone 2), and finally to run backward passing the finishing line at the first cone. Each time movement direction changed, subjects had to touch the respective cone with the nearest hand.

according to the lateral preference inventory (Coren, 1993). The subjects were instructed to aim at the middle of the goal and to act "as forcefully as possible." The rest between trials was 5 min. The mean of the three trials was analyzed.

Statistical analyses

Descriptive data are presented as group mean values ± standard deviations (SD). After normal distribution was examined (i.e., Kolmogorov–Smirnov test), an independent samples *t*-test was used to determine significant differences in pretesting values between groups. Subsequently, a 2 (group: CSTS, CSTU) × 2 (test: pre, post) analysis of variance with repeated measures on test was used. If baseline differences between groups were found, adjustments were performed with baseline measurements as covariate. The classification of effect sizes was determined by converting partial eta-squared to Cohen's *d*. The effect size is a measure of the effectiveness of a treatment and it helps to determine whether a statistically significant difference is a difference of practical concern. According to Cohen (1988), effect sizes can be classified as small ($0.00 \leq d \leq 0.49$), medium ($0.50 \leq d \leq 0.79$), and large ($d \geq 0.80$). The significance level was set at $P < 0.05$. All analyses were performed using Statistical Package for Social Sciences (SPSS) version 22.0 (SPSS Inc., Chicago, Illinois, USA).

Results

All subjects of the CSTS and CSTU groups received treatments as allocated. During the intervention period, one subject in the CSTS group dropped out because he left the youth training center. Another subject in the CSTU group discontinued the intervention because of personal reasons. Thus, 37 participants completed the training program and none reported any training or test-related injury. For the core strength training, CSTS and CSTU groups showed mean training frequencies of 2.4 and 2.3 sessions/week throughout the entire intervention period. Table 3 displays means and SDs for all analyzed variables. Except for one variable (i.e., higher kicking performance in CSTS compared with CSTU), there were no statistically significant differences in pretraining values between the two experimental groups.

Trunk muscle strength and activity

The statistical analysis revealed a significant main effect of test for trunk extensor MIF ($F_{1,62} = 5.79$, $P < 0.05$, $d = 0.86$) but not for trunk flexor MIF indicating that trunk extensor MIF increased in CSTS and CSTU groups. For both parameters, no significant main effect of group was detected. In our subsample analysis, no significant main effects of test and group ($P > 0.05$) were found for measures of trunk muscle activity (Table 3). In addition, no significant group × test interactions ($P > 0.05$) were observed for all measures related to trunk muscle strength and activity.

Athletic performance

For CMJ height, neither main effects of test and group nor a statistically significant group × test interaction was

Table 3. Changes in trunk muscle strength/activation and athletic performance following 9 weeks of core strength training performed on stable (CSTS) vs unstable surfaces (CSTU) in male elite youth soccer players

Variables	CSTS				Δ (%)	CSTU				Δ (%)	P value (d)		
	Pre		Post			Pre		Post			Test	Group	Group × test
	M	SD	M	SD		M	SD	M	SD				
Trunk muscle strength/activity													
Trunk flexor MIF (N)	656.5	92.3	681.0	89.3	3.7	624.4	99.6	617.7	97.6	−1.1	0.47 (0.26)	0.12 (0.56)	0.21 (0.45)
Trunk extensor MIF (N)	603.1	98.8	644.0	92.6	6.8	591.4	67.1	614.0	115.1	3.8	0.02 (0.86)	0.50 (0.25)	0.49 (0.25)
Flexor MAV (%)	47.9	9.5	56.8	4.4	18.4	53.2	11.4	55.6	12.7	4.6	0.11 (1.11)	0.70 (0.25)	0.34 (0.63)
Extensor MAV (%)	60.5	4.9	62.3	5.4	3.0	63.2	3.2	62.4	6.0	−1.3	0.83 (0.14)	0.49 (0.46)	0.56 (0.38)
Athletic performance													
CMJ height (cm)	36.0	3.4	35.5	3.2	−1.5	34.0	3.4	34.3	2.7	0.7	0.82 (0.09)	0.10 (0.61)	0.53 (0.24)
0–10-m time (s)	1.69	0.04	1.72	0.08	1.9	1.71	0.06	1.73	0.06	1.3	0.10 (0.98)	0.72 (0.20)	0.75 (0.18)
10–20-m time (s)	1.27	0.02	1.22	0.04	−3.6	1.28	0.05	1.25	0.02	−2.7	< 0.001 (2.56)	0.32 (0.58)	0.51 (0.38)
0–20-m time (s)	2.96	0.05	2.95	0.11	−0.5	2.99	0.11	2.97	0.07	−0.4	0.52 (0.37)	0.50 (0.39)	0.96 (0.03)
T test time (s)	9.7	0.4	9.7	0.5	−0.2	9.7	0.3	9.7	0.4	0.6	0.83 (0.09)	0.95 (0.02)	0.64 (0.19)
Kicking performance (km/h)	107.9	5.8	107.5	6.1	−0.3	101.3	6.8	103.4	6.3	2.1	0.003 (1.28)	0.61 (0.20)	0.61 (0.20)

CMJ, countermovement jump; d, effect size (i.e., Cohen's d); CSTS, core strength training performed on stable surface; CSTU, core strength training performed on unstable surface; MAV, mean amplitude voltage; MIF, maximal isometric force.

found (Table 3). In terms of sprint performance, our statistical calculations revealed that 10–20-m sprint time significantly decreased by test ($F_{1,26} = 21.33$, $P < 0.001$, $d = 2.56$). However, no main effect of group for 10–20-m sprint time and no main effects of test and group were found for 0–10-m and 0–20-m sprint time. In addition, no significant group × test interactions ($P > 0.05$) were observed for all measures of sprint performance (Table 3). For the T agility test, neither main effects of test and group nor statistically significant group × test interaction ($P > 0.05$) were detected (Table 3). Further, a significant main effect of test indicated that kicking performance improved in CSTS and CSTU groups following training ($F_{1,54} = 10.65$, $P < 0.01$, $d = 1.28$). However, no statistically significant group × test interaction ($P > 0.05$) was found (Table 3).

Discussion

To the authors' knowledge, this is the first study that investigated the effects of in-season CSTS compared with CSTU in combination with regular soccer training on trunk muscle strength/activation and athletic performance in healthy male elite youth soccer players. The main findings of this study were that (a) in addition to regular in-season soccer training, CSTS and CSTU represent feasible (i.e., mean attendance rate of 2.4 and 2.3 sessions/week throughout the entire intervention period, respectively) and safe (i.e., no core strength training-related injuries) training regimens for elite youth soccer players; (b) trunk muscle strength (i.e., MIF of trunk extensors) significantly improved, whereas trunk muscle activity did not change following 9 weeks in both CSTS and CSTU group; and (c) sprint time (i.e., 10–20 m) and kicking performance significantly improved after the

9-week training period without any significant difference between the CSTS and the CSTU groups while jumping, and agility performance did not significantly change.

The findings of the present study indicate significant improvements in trunk muscle strength (i.e., trunk extensor MIF) and proxies of athletic performance (i.e., 10–20 m sprint time, kicking performance) in male elite youth soccer players in the CSTS and CSTU group when added to regular soccer training. For core strength training using stable conditions (i.e., CSTS group), this is partly in line with the literature investigating the effects of CSTS on sport-specific skills in young athletes. For instance, Hoshikawa et al. (2013) reported that following both 6 months (4 sessions/week) of combined CSTS (e.g., prone and side bridging on elbows) and soccer training (e.g., technical drills, interval runs), as well as soccer training only, significant improvements were observed in 15-m sprint time in adolescent male outfield soccer players aged 12–13 years (combined group: $d = 1.12$, single soccer training group: $d = 0.78$). However, in contrast to our findings, significant gains in squat jump ($d = 0.66$) and CMJ height ($d = 1.24$) were observed in the combined training group as compared with the soccer only training group. This indicates that CSTS in combination with regular soccer training has additive value on variables of jump but not sprint performance as compared with single soccer training (Hoshikawa et al., 2013). In another study, it was shown that jump performance (i.e., reach difference in jump and reach test) was significantly higher in university- and state-level volleyball players following 9 weeks (5 sessions/week) of combined CSTS (e.g., bridging exercise, quadruped abdominal hollowing) and volleyball training as compared with volleyball training only ($d = 0.84$; Sharma et al., 2012). However, performance

in spike jump, CMJ, and squat jump was still similar in the combined training group and the isolated volleyball training group during posttest measurements ($d \leq 0.84$). Additionally, Tse et al. (2005) found significant group × test interactions for isometric trunk muscle endurance ($1.32 \leq d \leq 1.74$) in favor of combined CSTS (i.e., static/dynamic mobility and stability exercises) and rowing training compared with rowing training only in young adult rowers (mean age: 21 years). However, no changes were observed in any of the proxies for athletic performance (e.g., CMJ height, 10-m shuttle run time, 40-m sprint time). Given these inconsistencies in findings between our study and the aforementioned studies (Tse et al., 2005; Sharma et al., 2012; Hoshikawa et al., 2013), it seems reasonable to argue that training modalities (e.g., training duration and frequency) and/or other factors (e.g., age, prior experience) may modulate the effects of CSTS/CSTU combined with regular sport-specific training on measures of athletic performance.

Our study extends the existing literature in as much as we additionally investigated the role of surface instability during core strength training on trunk muscle strength/activation and athletic performance measures in male elite youth soccer players. Functionally, the rationale for incorporating unstable surfaces in strength-training exercises is that high levels of muscle activity occur during training (Behm & Colado-Sanchez, 2013). In fact, Vera-Garcia et al. (2000) reported higher muscle activation levels in rectus abdominis (15% of maximum voluntary contraction, $d = 1.50$) and external oblique muscles (5% of maximum voluntary contraction, $d = 0.66$) during crunches on a Swiss ball compared with a stable bench. Thus, the integration of unstable surfaces could provide extra stimuli to increase trunk muscle strength in a superior way as compared with stable surfaces (Behm et al., 2010b). However, similar to CSTS, only limited gains in trunk muscle strength (i.e., MIF of trunk extensors) and athletic performance (i.e., 10–20 m sprint time, kicking performance) were observed after CSTU in the present study. Of note, we assessed trunk muscle activity of two muscles only (i.e., rectus abdominis muscle, spinal erector muscle), which may explain why neuromuscular adaptations were lacking in both, CSTU and CSTS group. This is supported by Stanton et al. (2004) who investigated the effects of 6-week Swiss ball core training (e.g., alternating superman, supine Russian twist; 2 sessions/week) in male adolescent basketball and football players with a mean age of 16 years. Whereas trunk stability (i.e., Sahrmann test, Swiss ball prone stabilization test) improved because of Swiss ball core training compared with an active control group, no changes were observed in athletic performance measures (i.e., maximum oxygen uptake, running economy, running posture) and trunk muscle activity (i.e., m. rectus abdominis, m. obliquus externus, m. erector spinae). In terms of trunk muscle activity, Stanton et al. (2004) concluded that neural

adaptations may have occurred in other muscles, such as the pectoral or latissimus dorsi muscle following CSTU. In addition, we acknowledge that our EMG analyses could be underpowered (i.e., observed power: 22–50%) because of the rather small size of the subsample (i.e., $n = 7$ for the CSTU group and $n = 6$ for the CSTS group). A post-hoc power analysis was calculated for the parameter flexor and extensor MAV ($\alpha = 0.05$, $\beta = 0.20$, statistical power $1 - \beta = 0.8$, $d = 0.3$). The analysis revealed a total sample size of 24 subjects to obtain statistically significant results.

What could be the underlying reasons for the observed limited effects of CSTS/CSTU in combination with regular soccer training on measures of athletic performance? First, on a behavioral level, cross-sectional studies revealed statistically significant but small-sized correlation coefficients ($-0.60 \leq r \leq 0.68$) between trunk muscle strength and proxies of athletic performance (i.e., short-distance sprint, agility, jump performance; Nesser et al., 2008; Sharma et al., 2012; Prieske et al., 2014a). Second, on a neuromuscular level, a recent study demonstrated significant but small-sized relationships between activation levels of trunk and lower limb muscles ($0.45 \leq r \leq 0.68$) during jump tasks (Prieske et al., 2014a). Taken together, significant but small-sized correlation coefficients between trunk muscle strength/activation and lower limb muscle performance/ activation during the performance of athletic tasks imply that training-induced adaptations in trunk muscle performance/activation levels will not necessarily be transferred to limb muscle performance/activation and/or vice versa, which is in contrast with the often reported assumption that proximal trunk stability supports distal limb contraction torques (Behm et al., 2010b) and mobility (Kibler et al., 2006).

Further, to the authors' knowledge, there is only one study available that directly compared the effects of CSTS vs CSTU in combination with regular soccer training on trunk muscle strength and measures of athletic performance in healthy but untrained adolescents (mean age: 14 years; Granacher et al., 2014). In that study, improvements in trunk muscle strength (i.e., ventral side: $d = 1.52$, lateral left side: $d = 0.94$) and athletic performance (i.e., jumping sideways: $d = 2.14$, Y balance test: $d = 0.92$) were reported following 6 weeks of CSTS and CSTU (2 sessions/week). However, only limited additional improvements have been found for the stand-and-reach test ($d = 1.08$) after CSTU compared with CSTS. In contrast with the study of Granacher et al. (2014), male elite youth athletes were investigated in the present study. Thus, it can be speculated that the training status of our subjects may have contributed to the findings of no additional enhancements following CSTU as compared with CSTS. In fact, the adaptive reserve for strength gains appears to be lower in highly trained subjects compared with novices because of a leveling off with increasing training status (Rhea et al., 2003). For

instance, significant increases in leg extensor MIF were observed in novices but not in strength-trained athletes following 21 weeks of strength training (2 sessions/week) when similar intensities were used during the training period (Ahtiainen et al., 2003). Of note, instability conditions can impair force (Anderson & Behm, 2004), power (Drinkwater et al., 2007; Prieske et al., 2013), and/or movement velocity (Drinkwater et al., 2007) during performance. Thus, CSTU may be inappropriate to induce additional training-related strength gains in highly trained youth soccer players because of impaired performance output on unstable surfaces (Behm et al., 2010a). Moreover, in terms of coordinative adaptations, enhanced performance of athletes in perception, anticipation, and decision making is dependent on the amount of practice and specific for the practiced movement task (Yarrow et al., 2009). Given the high volume of the participants' soccer training in the present study (i.e., six training sessions per week each lasting approximately 90 min on a regular basis), CSTS and CSTU were performed only 2–3 times per week during the 9-week intervention period. Thus, it can be speculated that volume of CSTU was inappropriate to induce additional coordinative performance gains (e.g., jump, agility performance) in highly trained youth soccer players.

Limitations of the study

We acknowledge that no active (i.e., soccer training only) or passive control group (no training) was included in this study, which represents a limitation when interpreting our findings. Yet, the inclusion of a passive control group is impossible in an athletic setting because we cannot expect athletes to stop training for 9 weeks. Additionally, the inclusion of an active control group is hardly feasible in this specific case because core-strengthening exercises (e.g., crunch, side bridge, back extension) have been proposed to be an essential component in youth athletes' regular conditioning program. From a health-related perspective, this is of particular importance for young athletes to tolerate high training loads (Myer et al., 2008; Soligard et al., 2008). Consequently, we cannot expect elite youth athletes to conduct soccer training without performing core exercises for 9 weeks. This is of particular relevance when training is conducted during in-season as in the present study

because injury prevention routines such as core strength training should be established on a regular basis specifically in youth athletes (Steffen et al., 2013). Given these circumstances, we specifically aimed at investigating the effects of traditional core exercises performed on stable surfaces as compared with core exercises performed on unstable elements. By doing so, none of the participating athletes had a disadvantage regarding the applied exercises that were performed during training. More specifically, coaches and athletes did not have to refrain from core-strengthening exercises over the course of the study simply because they participated in the study.

Perspectives

Incorporating unstable surfaces in strength-training exercises is highly recommended, in particular in youth (Behm & Colado-Sanchez, 2013). Based on the present findings, this study illustrates that in-season core strength training under stable and unstable conditions is a feasible (attendance rate of 2.4 training sessions/week in CSTS group and 2.3 sessions/week in CSTU group) and safe (i.e., no core strength training-related injuries) training modality in male elite youth soccer players. Further, following both core strength-training programs together with regular soccer training, similar enhancements in trunk muscle strength (i.e., trunk extensors) and proxies of athletic performance (i.e., sprint time, kicking performance) were observed. Consequently, the combination of regular soccer training together with either core strengthening on stable or unstable surfaces may successfully be implemented in elite youth soccer players to improve athletic performances. Further, using unstable devices and/or surfaces during core strength training guarantees training stimulus variety with no disadvantage compared with stable devices/surfaces.

Key words: Elite sports, jumping, agility, sprint, ball speed, electromyography.

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