Feedback cues improve the alignment and technique of children performing ACL injury prevention exercises

Daphne I Ling, Caroline Boyle, Joseph Janosky, Brenda Chang, Naomi Roselaar, James Kinderknecht, Robert G Marx

► Additional material is published online only. To view please visit the journal online (http://dx.doi.org/10.1136/jisakos-2020-000475).

Sports Medicine Institute, Hospital for Special Surgery, New York, New York, USA

Correspondence to
Dr Daphne I Ling, Sports Medicine Institute, Hospital for Special Surgery, New York, New York, USA; lingd@hss.edu

Accepted 27 August 2020
Published Online First 28 October 2020

ABSTRACT

Objectives The appropriateness of neuromuscular training exercises across different age groups has not yet been investigated, particularly in younger children. The purpose of this study was to determine which neuromuscular training exercises can be performed with proper neutral alignment in various age groups.

Methods Seven exercises were selected for evaluation in children ranging from 8 to 17 years of age who were recruited from schools and youth sports organisations. Participants completed two trials of each exercise and were judged on maintaining neutral body alignment after receiving visual/verbal instruction on the first trial and feedback cues on the second trial. Three evaluators judged each exercise, which was deemed as correct when at least two evaluators agreed that neutral alignment was maintained. Comparisons were made across ages and between sex using the χ^2 test or Fisher's exact test. The proportions of participants who performed the exercise correctly were also compared before and after feedback cues were provided.

Results A total of 360 participants were evaluated (8–11 years: 165, 54% female; 12–15 years: 136, 40% female, 16–17 years: 59, 53% female). There were no significant differences in performance across ages and sex for nearly all exercises. The majority of children were not able to complete the exercises with proper alignment. The use of feedback cues significantly increased the proportion of participants who correctly completed the exercise ($p<0.001$).

Conclusions These results demonstrate the importance of training coaches and physical education teachers to provide cues that reinforce proper technique during anterior cruciate ligament injury prevention exercises. Children should perform common neuromuscular training exercises with feedback on proper technique.

Level of evidence IV (case series).

What are the new findings

- Children should perform common neuromuscular training exercises with feedback on proper technique for anterior cruciate ligament injury prevention exercises.
- The results demonstrate the importance of training coaches and physical education teachers to provide cues that reinforce proper technique.

INTRODUCTION

Anterior cruciate ligament (ACL) rupture is one of the most common sports-related knee injuries, with an estimated 250 000 injuries per year in the USA.[1 2] The standard surgical treatment is reconstruction of the ACL, but while clinical outcomes have improved over the years, there are still significant health consequences to ACL injuries.[3] Although a majority of patients (81%–85%) return to some physical activity after ACL reconstruction (ACLR), only 55%–65% return to their preinjury level of competition.[4 5] There is also an increased risk of premature osteoarthritis and additional knee surgery, especially when the injury occurs at a young age.[6–9] Due to the long-term consequences of ACL injuries, the ideal strategy is to avoid them by using prevention programmes that can decrease injury risk.

Several injury prevention programmes have been developed to decrease the occurrence of ACL injuries. A meta-analysis of overlapping meta-analyses reported that these programmes resulted in a 50% risk reduction in ACL injuries and an even higher reduction (67%) in non-contact ACL injuries in female athletes, who are at greater risk due to anatomical, biomechanical or physiological differences.[10] There is ample evidence showing injury prevention programmes that incorporate balance, plyometric and strength training and that are performed 2–3 times per week for at least 10–15 min have been successful in decreasing injury rates.[11–13] While injury prevention programmes have been developed for a variety of sports, the exercises included often involve complex instructions and movement patterns. Not surprisingly, young children require more attention and feedback when learning new tasks.[14] It remains unclear whether the exercises are beyond the level of comprehension or perhaps not challenging enough for children in the younger age groups.[15]

Injury prevention programmes that have been effective for improving movement patterns and landing mechanics in older athletes have had limited success in younger athletes.[16 17] In one study, high school participants improved their landing technique more than pre-high school participants.[16] Another study evaluated a modified paediatric programme for children under age 12 that consisted of greater exercise variety and progressions, more feedback and reduced frequency. In contrast to the traditional programme that was developed for older athletes, participants using the paediatric version did not improve on balance and vertical jump height.[15] Thus, younger children may require more specialised training in basic movement patterns. FIFA 11+Kids was one of the first programmes designed for youth populations (<13

To cite: Ling DI, Boyle C, Janosky J, *et al*. *J ISAKOS* 2021;**6**:3–7.

years of age) that takes into account physical maturity and age-specific injury mechanisms.[18] This programme consists of seven different exercises across three progressive skill levels that focus on spatial orientation, general stability and movement coordination and proper falling technique. A randomised controlled trial found that after 4 weeks of participating in FIFA 11+Kids, athletes showed improvements on jump performance, balance and agility tests.[19]

The appropriateness of injury prevention exercises across different age groups has not yet been investigated in adolescent and preadolescent children. Exercises that are too difficult will likely not be incorporated into warm-up routines, thereby reducing adherence and negating their effect on preventing injuries. While ability may vary within age groups, chronological age is an important consideration for determining who plays on the same team. Maintaining neutral alignment and using proper technique may reduce the biomechanical risk factors that can lead to injury. The purpose of this study was to determine which neuromuscular training exercises can be performed correctly (with proper alignment) by individuals of various age groups. Our hypothesis is that athletes between the ages of 8–17 will differ in their ability to perform the exercises with correct technique, with a progression in the appropriateness of exercise difficulty as children get older. Having injury prevention programmes that are appropriate for a particular age group may help facilitate their adoption and maximise their impact on injury reduction.

METHODS

Participants

Written, informed parental consent and child assent were obtained from every participant. Participants between the ages of 8–17 years were enrolled from schools and youth sports organisations in the greater New York City area. These children were from physical education classes or recreational teams. Participants were excluded if they were unable to understand the visual/verbal instructions and cues provided by the investigators or if they had a self-reported, existing musculoskeletal condition.

Procedures

The Sports Safety Program at our institution has developed unique neurodynamic warm-up programmes that coaches can customise according to the skill/competition level and sport type. Seven different exercises were selected from these programmes for the participants ages 8–17 years, with increasing levels of difficulty of the same exercise for older children. These exercises were based on the five phases of the neurodynamic warmup: movement preparation, agility, lower-extremity strengthening, plyometrics and core stability. Two exercises each were chosen for the lower-extremity strengthening and plyometrics phases since these exercises tend to be the most challenging. The exercises performed in the 8–9 age group were the same as those in the 10–11 age group. Similarly, the exercises performed in the 12–13 age group was the same as those in the 14–15 age group. The 16–17 age group performed the most difficult exercises. Thus, the results were categorised into three age groups: 8–11, 12–15 and 16–17.

The participants performed each exercise twice. Prior to the first attempt, the investigators used visual and verbal instructions when explaining how to perform the exercise. One person provided instructions to small groups ranging from 5 to 10 children depending on the number at each data collection session. Verbal instructions were followed by a live demonstration of each exercise: for example, 'Run in a figure 8 motion through these cones' (Figure-8 Run) or 'Begin in an athletic stance or ready position and then shuffle feet laterally while repeatedly raising arms overhead' (Side Shuffle). On the second attempt, the investigators provided visual and verbal cues that reinforced correct movement technique: for example, 'Keep your head in line with your body' or 'Land softly and quietly' or 'Hips, knees, and toes point straight ahead as you run'. Please see the online supplemental appendix 1 for a script of the instructions and cues for each exercise in each age group. After each attempt, three experienced sports medicine practitioners (physical therapists, athletic trainers and certified strength and conditioning specialists), who faced the participants, determined if the participant performed the exercise correctly by maintaining neutral cervical-thoracic spine alignment, neutral lumbopelvic complex alignment and neutral lower extremity alignment. For instance, neutral alignment of the lower extremity is indicated by straight alignment of the hip, knee and ankle. Exercise technique was judged to be correct when at least two of the three evaluators determined that neutral alignment in all three body regions was maintained during the performance of each exercise.

Sample size calculation

Using an inequality test for one proportion with a null hypothesis that 50% of participants are able to perform the exercise correctly, we were able to achieve a power of 0.90 to detect an alternative proportion of 80% at an alpha level of 0.05 with 28 subjects. Thus, the target enrolment for this study was 28 males and 28 females for all five age categories (8–9, 10–11, 12–13, 14–15, 16–17 years) for a total target enrolment of 280 participants.

Statistical analysis

Results for participants in the 8–11, 12–15 and 16–17 age groups were analysed separately. For each exercise, comparisons between ages and sex were made using the χ^2 or Fisher's exact test as appropriate. Proportions of participants who could perform the exercise correctly before and after cues were compared using a one-sample test of proportions. The kappa statistic was used to measure inter-rater reliability among the nine evaluators. Analyses were conducted using SAS V.9.4 (SAS, Cary, North Carolina, USA).

RESULTS

A total of 360 participants were evaluated in this study: 71 in the 8–9 age category (55% female), 94 in the 10–11 age category (54% female), 79 in the 12–13 age category (38% female), 57 in the 14–15 age category (37% female) and 59 in the 16–17 age category (53% female). There were no significant differences in exercise performance between participants ages 8–9 and 10–11 (online supplemental appendix 2) or ages 12–13 and 14–15 (online supplemental appendix 3). Similarly, there were no significant differences between the proportions of males and females who completed the exercises correctly when considering both performance after instructions only and after instructions plus cues for any of the age groups (tables 1–3).

For all exercises in every age group, there was a less than 50% success rate after the administration of instructions alone. The use of feedback cues significantly increased the proportion of participants who correctly completed the exercises (table 4). However, there were some exercises in each age group for which a majority of participants could not perform the exercise with proper alignment even after cues were administered. In the 8–11 age group, the lowest proportions were seen for the scissor

Table 1 Proportion (%) of males and females ages 8–11 years who performed exercises correctly with proper alignment

Exercise		Males	Females	P value*
Forward/Backward Jog	Exercise instruction	32.0	35.6	0.74
	Technique cues	69.3	73.3	0.61
Figure-8 Run (narrow)	Exercise instruction	48.0	50.0	0.88
	Technique cues	82.7	77.8	0.56
Level 1 Lunge	Exercise instruction	2.7	7.8	0.18
	Technique cues	32.0	23.3	0.23
Level 1 Double leg squat	Exercise instruction	21.3	16.7	0.55
	Technique cues	49.3	41.1	0.35
Level 1 Broad jump	Exercise instruction	8.0	13.3	0.32
	Technique cues	17.3	25.6	0.26
Level 1 Scissor jump	Exercise instruction	1.3	4.4	0.38
	Technique cues	4.0	10.0	0.23
Level 1 Side plank	Exercise instruction	29.3	22.2	0.37
	Technique cues	58.7	61.1	0.75

*χ^2 p values represent the comparison between males and females.

Table 3 Proportion (%) of males and females ages 16–17 years who performed exercises correctly with proper alignment

Exercise		Males	Females	P value*
Carioca	Exercise instruction	42.9	9.7	0.003
	Technique cues	75.0	54.8	0.11
Forward/Backward Angled Run	Exercise instruction	28.6	25.8	0.81
	Technique cues	82.1	71.0	0.31
Level 3 Lunge	Exercise instruction	3.6	6.5	0.62
	Technique cues	53.6	45.2	0.52
Level 2 Double leg squat	Exercise instruction	42.9	54.8	0.36
	Technique cues	71.4	83.9	0.25
Level 2 Broad jump	Exercise instruction	14.3	25.8	0.27
	Technique cues	46.4	58.1	0.37
Level 3 Scissor jump	Exercise instruction	21.4	12.9	0.38
	Technique cues	60.7	35.5	0.05
Level 3 Side plank	Exercise instruction	28.6	25.8	0.81
	Technique cues	50.0	54.8	0.71

*χ^2 p values represent the comparison between males and females.

jump, followed by the broad jump, lunge and double-leg squat. In the 12–15 age group, the lowest proportions were seen for the scissor jump, lunge, and broad jump. In the oldest 16–17 age group, the lowest proportions were found for the lunge and scissor jump at 49% and 48%, respectively. The kappa statistics for multiple evaluators were k=0.31 in the 8–11 age group, k=0.42 in the 12–15 age group and k=0.31 in the 16–17 age group, indicating fair to moderate agreement.

DISCUSSION

In general, injury prevention programmes have used a 'one size fits all' approach and the same exercises have been recommended to athletes of all ages. There is a paucity of studies in younger athletes, particularly those under 12 years of age. The purpose of this study was to determine whether children 8–17 years of age can perform common neuromuscular training exercises correctly. For almost all exercises in this study, participants' ages 8–9 and 10–11 years were able to maintain proper alignment with equal ability. The same applied to participants ages 12–13 and 14–15 years. There was also no significant difference between male and female participants who completed exercises correctly across the age groups. Perhaps the most surprising finding was that the majority of children were not able to complete any of the exercises with proper technique. Almost every exercise had a less than 50% success rate. However, the addition of visual and verbal cues significantly increased the proportion of children who correctly completed the exercises across all ages. These results call attention to the urgent need for coaches and physical educators to provide appropriate technique cues when implementing injury prevention programmes. Providing exercise instruction alone will minimise the beneficial impact on injury reduction.

A few studies have showed that providing cues had beneficial effects on reducing ACL injuries,[20–22] including a meta-regression that found feedback cues (either verbal or video review) to be one of the critical components of neuromuscular training programmes that resulted in significant injury reduction.[13] Other studies have also varied the ways in which cues are administered. In one study, the investigators used a trainer to provide both verbal and visualisation cues for jumping exercises.[23] Another study of female handball players relied on the practice partner to provide feedback on the movement quality.[24] In the same study, the incorporation of verbal cues was one of several modifications made after the first season that led to a reduction in ACL injuries in the subsequent season. While the independent effect of providing cues is unclear in that study, we were able to measure the direct changes in proper alignment after cues were administered in our current study.

In a meta-regression, neuromuscular training programmes had the greatest injury risk reduction in female athletes who were in their early teenage years (<14) compared with older age groups.[13] Another biomechanics study concluded that the FIFA 11+ programme was more effective in reducing known risk factors for ACL injury, namely knee valgus angle and moment on jump landings, in preadolescent (10–12 years) compared with adolescent female athletes.[25] These findings highlight the importance of getting athletes of younger ages to learn correct movement patterns and the need for developing age-specific injury prevention programmes. Movement literacy is the basis for general physical development and motor learning, and it would be beneficial to lay the foundation in young athletes sooner than later.[26 27] Furthermore, the availability of exercises that are suitable for a particular age group may improve adherence to injury

Table 2 Proportion (%) of males and females ages 12–15 years who performed exercises correctly with proper alignment

Exercise		Males	Females	P value*
Side Shuffle	Exercise instruction	42.4	45.1	0.76
	Technique cues	78.8	80.4	0.83
Figure-8 Run (wide)	Exercise instruction	43.5	39.2	0.62
	Technique cues	81.2	74.5	0.36
Level 2 Lunge	Exercise instruction	10.6	11.8	0.83
	Technique cues	36.5	31.4	0.55
Level 2 Double leg squat	Exercise instruction	42.4	29.4	0.13
	Technique cues	61.2	76.5	0.07
Level 2 Broad jump	Exercise instruction	12.9	11.8	0.84
	Technique cues	45.9	45.1	0.93
Level 2 Scissor jump	Exercise instruction	10.6	5.9	0.35
	Technique cues	31.8	15.7	0.04
Level 2 Side plank	Exercise instruction	55.3	31.4	0.007
	Technique cues	83.5	72.6	0.13

*χ^2 p values represent the comparison between males and females.

Table 4 Proportion (%) of participants ages 8–11, 12–15 and 16–17 who performed exercises correctly before and after administration of cues (all comparisons p<0.001 unless otherwise noted)

Ages 8–11		
Forward/Backward Jog	Exercise instruction	33.9
	Technique cues	71.5
figure 8 Run (narrow)	Exercise instruction	49.1
	Technique cues	80.0
Level 1 Lunge	Exercise instruction	5.5
	Technique cues	27.3
Level 1 Double leg squat	Exercise instruction	18.8
	Technique cues	44.9
Level 1 Broad jump	Exercise instruction	10.9
	Technique cues	21.8
Level 1 Scissor jump*	Exercise instruction	3.0
	Technique cues	7.3
Level 1 Side plank	Exercise instruction	25.5
	Technique cues	60.0
Ages 12–15		
Side shuffle	Exercise instruction	43.4
	Technique cues	79.4
Figure 8 Run (wide)	Exercise instruction	41.9
	Technique cues	78.7
Level 2 Lunge	Exercise instruction	11.0
	Technique cues	34.6
Level 2 Double leg squat	Exercise instruction	37.5
	Technique cues	66.9
Level 2 Broad jump	Exercise instruction	12.5
	Technique cues	45.6
Level 2 Scissor jump	Exercise instruction	8.8
	Technique cues	25.7
Level 2 Side plank	Exercise instruction	46.3
	Technique cues	79.4
Ages 16–17		
Carioca	Exercise instruction	25.4
	Technique cues	64.4
Forward/Backward angled run	Exercise instruction	27.1
	Technique cues	76.3
Level 3 Lunge	Exercise instruction	5.1
	Technique cues	49.2
Level 2 Double leg squat	Exercise instruction	49.2
	Technique cues	78.0
Level 2 Broad jump	Exercise instruction	20.3
	Technique cues	52.5
Level 3 Scissor jump	Exercise instruction	17.0
	Technique cues	47.5
Level 3 Side Plank	Exercise instruction	27.1
	Technique cues	52.5

*χ^2 p=0.03.

prevention programmes and, more importantly, have a real impact on reducing injuries.

Thus, the inclusion of developmentally appropriate exercises and the ability to correct movement deficiencies are important considerations when designing injury prevention programmes for young athletes based on chronological age. For exercises that are too difficult for their athletes, coaches can use a less challenging option. On the other hand, for exercises that are not challenging enough, coaches can choose to increase the difficulty. One study evaluating the Sportsmetrics programme in female soccer players failed to see significant changes in landing mechanics after 8 weeks compared with controls.[17] The authors of this study hypothesised that their results may be due to the study population (mean age 10 years) who were unable to perform some of the exercises. In our study, the lunge and complex jumps such as the scissor and broad jump had the lowest proportions of correct alignment, even with the addition of feedback cues. Similarly, the investigators for the Sportsmetrics study removed the supine hamstring (bridge) when younger participants were physically unable to perform this exercise correctly.[17] The length of the exercise as well as the intensity and duration of the injury prevention programme have also been mentioned as important considerations for maintaining proper form when performing an exercise.[15 17]

This study evaluated the ability to maintain neutral spinal and lower extremity alignment in young athletes with and without feedback cues, and the population that we used was a strength of the study. Children were recruited from physical education classes and recreational sports teams to increase the external validity of our findings. Recruiting from higher-level teams would likely result in a study sample with better movement competency and not provide the same type of normative data for the general youth population. The study also had several limitations. The agreement between evaluators was only moderate/fair and could be due to the large number of staff members that was required in order to conduct this study. Only certain exercises were evaluated, and the levels of difficulty for individual age groups were decided based on clinical judgement. For certain exercises, the language used in the instructions could be too complex for younger children to understand. Any improvement on the second trial may just be due to better understanding of how to perform the exercise. In addition, this study was cross-sectional in nature, as visual and verbal cues were only given once. It is possible that the use of cues over time will increase the proportion of children who complete the exercises with proper technique and alignment. Future research directions may include a longitudinal study on repeated feedback for long-term retention of correct movement quality, as well as a head-to-head comparison of injury prevention programmes that use instructions alone or both instructions plus cues and their impact on injury reduction.

CONCLUSION

Most neuromuscular training exercises had a less than 50% success rate for proper alignment in children 8–17 years of age. The use of verbal and visual cues significantly increased the proportions of participants who correctly completed the exercise. Children should perform common neuromuscular training exercises with feedback on proper technique.

Twitter Daphne I Ling @LingDaphne

Contributors DIL was responsible for conceptualisation, data curation, methodology, statistical analysis, project administration, supervision and writing the manuscript. CB was responsible for data curation, methodology, project administration, supervision and reviewing the manuscript. JJ was responsible for conceptualisation, data curation, methodology, project administration, supervision and reviewing the manuscript. BC was responsible for data curation, data curation, statistical analysis and reviewing the manuscript. NR was responsible for data curation, methodology, project administration, supervision and reviewing the manuscript. JK was responsible for conceptualisation, methodology, supervision and reviewing the manuscript. RGM was responsible for conceptualisation, methodology, supervision and reviewing the manuscript.

Funding The authors have not declared a specific grant for this research from any funding agency in the public, commercial or not-for-profit sectors.

Competing interests None declared.

Patient consent for publication Not required.

Ethics approval This study was approved by the Institutional Review Board (#2016–855).

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement Data are available on reasonable request.

ORCID iD
Daphne I Ling http://orcid.org/0000-0003-4415-2471

REFERENCES

1 Griffin LY, Albohm MJ, Arendt EA, *et al*. Understanding and preventing noncontact anterior cruciate ligament injuries: a review of the HUNT Valley II meeting, January 2005. *Am J Sports Med* 2006;34:1512–32.
2 Buller LT, Best MJ, Baraga MG, *et al*. Trends in anterior cruciate ligament reconstruction in the United States. *Orthop J Sports Med* 2015;3:232596711456366.
3 Paterno MV, Rauh MJ, Schmitt LC, *et al*. Incidence of contralateral and ipsilateral anterior cruciate ligament (ACL) injury after primary ACL reconstruction and return to sport. *Clin J Sport Med* 2012;22:116–21.
4 Ardern CL, Taylor NF, Feller JA, *et al*. Fifty-five per cent return to competitive sport following anterior cruciate ligament reconstruction surgery: an updated systematic review and meta-analysis including aspects of physical functioning and contextual factors. *Br J Sports Med* 2014;48:1543–52.
5 Waldén M, Hägglund M, Magnusson H, *et al*. ACL injuries in men's professional football: a 15-year prospective study on time trends and return-to-play rates reveals only 65% of players still play at the top level 3 years after ACL rupture. *Br J Sports Med* 2016;50:744–50.
6 Kocher MS, Saxon HS, Hovis WD, *et al*. Management and complications of anterior cruciate ligament injuries in skeletally immature patients: survey of the Herodicus Society and the ACL Study Group. *J Pediatr Orthop* 2002;22:452–7.
7 Lohmander LS, Ostenberg A, Englund M, *et al*. High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury. *Arthritis Rheum* 2004;50:3145–52.
8 Lohmander LS, Englund PM, Dahl LL, *et al*. The long-term consequence of anterior cruciate ligament and meniscus injuries: osteoarthritis. *Am J Sports Med* 2007;35:1756–69.
9 Vavken P, Murray MM. Treating anterior cruciate ligament tears in skeletally immature patients. *Arthroscopy* 2011;27:704–16.
10 Webster KE, Hewett TE. Meta-Analysis of meta-analyses of anterior cruciate ligament injury reduction training programs. *J Orthop Res* 2018;36:2696–708.
11 Alentorn-Geli E, Myer GD, Silvers HJ, *et al*. Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 2: a review of prevention programs aimed to modify risk factors and to reduce injury rates. *Knee Surg Sports Traumatol Arthrosc* 2009;17:859–79.
12 Monajati A, Larumbe-Zabala E, Goss-Sampson M, *et al*. The effectiveness of injury prevention programs to modify risk factors for non-contact anterior cruciate ligament and hamstring injuries in uninjured team sports athletes: a systematic review. *PLoS One* 2016;11:e0155272.
13 Sugimoto D, Myer GD, Barber Foss KD, *et al*. Critical components of neuromuscular training to reduce ACL injury risk in female athletes: meta-regression analysis. *Br J Sports Med* 2016;50:1259–66.
14 Sullivan KJ, Kantak SS, Burtner PA. Motor learning in children: feedback effects on skill acquisition. *Phys Ther* 2008;88:720–32.
15 DiStefano LJ, Padua DA, Blackburn JT, *et al*. Integrated injury prevention program improves balance and vertical jump height in children. *J Strength Cond Res* 2010;24:332–42.
16 DiStefano LJ, Padua DA, DiStefano MJ, *et al*. Influence of age, sex, technique, and exercise program on movement patterns after an anterior cruciate ligament injury prevention program in youth soccer players. *Am J Sports Med* 2009;37:495–505.
17 Grandstrand SL, Pfeiffer RP, Sabick MB, *et al*. The effects of a commercially available warm-up program on landing mechanics in female youth soccer players. *J Strength Cond Res* 2006;20:331–5.
18 Rössler R, Donath L, Bizzini M, *et al*. A new injury prevention programme for children's football--FIFA 11+ Kids--can improve motor performance: a cluster-randomised controlled trial. *J Sports Sci* 2016;34:549–56.
19 Pomares-Noguera C, Ayala F, Robles-Palazón FJ, *et al*. Training effects of the FIFA 11+ kids on physical performance in youth football players: a randomized control trial. *Front Pediatr* 2018;6:40.
20 Gilchrist J, Mandelbaum BR, Melancon H, *et al*. A randomized controlled trial to prevent noncontact anterior cruciate ligament injury in female collegiate soccer players. *Am J Sports Med* 2008;36:1476–83.
21 LaBella CR, Huxford MR, Grissom J, *et al*. Effect of neuromuscular warm-up on injuries in female soccer and basketball athletes in urban public high schools: cluster randomized controlled trial. *Arch Pediatr Adolesc Med* 2011;165:1033–40.
22 Olsen O-E, Myklebust G, Engebretsen L, *et al*. Exercises to prevent lower limb injuries in youth sports: cluster randomised controlled trial. *BMJ* 2005;330:449.
23 Hewett TE, Lindenfeld TN, Riccobene JV, *et al*. The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study. *Am J Sports Med* 1999;27:699–706.
24 Myklebust G, Engebretsen L, Braekken IH, *et al*. Prevention of anterior cruciate ligament injuries in female team handball players: a prospective intervention study over three seasons. *Clin J Sport Med* 2003;13:71–8.
25 Thompson-Kolesar JA, Gatewood CT, Tran AA, *et al*. Age influences biomechanical changes after participation in an anterior cruciate ligament injury prevention program. *Am J Sports Med* 2018;46:598–606.
26 Lloyd RS, Oliver JL, Faigenbaum AD, *et al*. Long-Term athletic development- Part 1: a pathway for all youth. *J Strength Cond Res* 2015;29:1439–50.
27 Lloyd RS, Oliver JL, Faigenbaum AD, *et al*. Long-Term athletic development, part 2: barriers to success and potential solutions. *J Strength Cond Res* 2015;29:1451–64.

Appendix 1

Ages 8-11: Exercise instructions and cues

1. Jogging - Forward & Backward

INSTRUCTION: Slowly jog forward and backward.

CUES:

- Stand up tall as you run keeping your head in line with your body
- Hips, knees and toes point straight ahead as you run
- See the field/court from as high as possible

2. Figure 8 Run - Narrow

INSTRUCTION: Run in a figure 8 motion through a series of cones or markers.

CUES:

- Stand up tall as you run keeping your head in line with your body
- Hips, knees and toes point straight ahead as you run
- See the field/court from as high as possible

3. Lunge 1

INSTRUCTION: Stand in an upright position with your hands held in front of your body and feet at shoulder width. Step forward with one foot and lower your opposite knee toward the floor. Slowly return to the starting position and repeat this activity with the opposite leg.

CUES:

- Keep your head in line with your body
- Brace your body as you would against the wind or a wave in the ocean
- Hip, knee and ankle joints stacked on top of each other as you move

4. Double Leg Squat 1

INSTRUCTION: Stand in an upright position with your hands held in front of your body and feet at shoulder width. Lower your body by bending at your hips and knees until your knees are close to a 90 degree angle. Slowly return to the starting position.

CUES:

- Keep your head in line with your body
- Brace your body as you would against the wind or a wave in the ocean
- Hip, knee and ankle joints stacked on top of each other as you move

- Open (break) a glass door with your butt

5. Broad Jumps 1

INSTRUCTION: Stand in an upright position with your arms at your sides and elbows bent. Quickly swing both arms backward and then forward as you jump, landing with both legs at the same time. Pause briefly before jumping again.

CUES:

- Keep your head in line with your body
- Brace your body as you would against the wind or a wave in the ocean
- Hip, knee and ankle joints stacked on top of each other as you move
- Land softly and quietly
- Open (break) a glass door with your butt when you land

6. Scissor Jumps 1

INSTRUCTION: Stand with one foot in front of the other with your arms at your sides and elbows bent. Jump up and switch your front foot to the back and your back foot to the front. Repeat this movement with the opposite legs.

CUES:

- Keep your head in line with your body
- Brace your body as you would against the wind or a wave in the ocean
- Hip, knee and ankle joints stacked on top of each other as you move
- Land softly and quietly

7. Side Plank 1

INSTRUCTION: Lie on your side with the elbow of your bottom arm directly under your shoulder. Stack your feet and put your top hand on your hip. Push down through your forearm and feet and lift your body from the floor.

CUES:

- Keep your head in line with your body
- Brace your body as you would against the wind or a wave in the ocean
- Squeeze your butt
- Form a perfectly straight line with your body from your head to your feet

Ages 12-15: Exercise instructions and cues

1. Side Shuffle

INSTRUCTION: Begin in an athletic stance or ready position and then shuffle feet laterally while repeatedly raising arms overhead.

CUES:

- Keep your head in line with your body as you move
- Brace your body as you would against the wind or a wave in the ocean
- Hips, knees and toes point straight ahead as you move

2. Figure 8 Run - Wide

INSTRUCTION: Run in a figure 8 motion through a series of cones or markers.

CUES:

- Stand up tall as you run keeping your head in line with your body
- Hips, knees and toes point straight ahead as you run
- See the field/court from as high as possible

3. Lunge 2

INSTRUCTION: Begin by standing in an upright position with your hands held in front of your body and feet at shoulder width. Step forward with one foot and lower your opposite knee toward the floor. Slowly return to the starting position and then step backward with the same foot and lower your knee toward the floor. Repeat this activity with the opposite leg.

CUES:

- Keep your head in line with your body
- Brace your body as you would against the wind or a wave in the ocean
- Hip, knee and ankle joints stacked on top of each other as you move

4. Double Leg Squat 2

INSTRUCTION: Begin by in a standing upright position with your hands held behind your head and feet at shoulder width. Squat by bending at your knees and hips until your knees are close to a 90 degree angle. Slowly return to the starting position and repeat this movement for the allotted time.

CUES:

- Keep your head in line with your body
- Brace your body as you would against the wind or a wave in the ocean
- Hip, knee and ankle joints stacked on top of each other as you move

- Open (break) a glass door with your butt

5. Broad Jump 2

INSTRUCTION: Begin by standing in an upright position with your arms at your sides and elbows bent. Quickly swing both arms backward and then forward as you jump forward, landing with both legs at the same time. Quickly repeat this movement for the allotted time.

CUES:

- Keep your head in line with your body
- Brace your body as you would against the wind or a wave in the ocean
- Hip, knee and ankle joints stacked on top of each other as you move
- Land softly and quietly
- Open (break) a glass door with your butt when you land

6. Scissor Jump 2

INSTRUCTION: Begin in a lunge position with your hands placed behind your head. Jump vertically into the air and switch your front foot to the back and your back foot to the front. Return to a lunge position after you land. Repeat this movement for the allotted time.

CUES:

- Keep your head in line with your body
- Brace your body as you would against the wind or a wave in the ocean
- Hip, knee and ankle joints stacked on top of each other as you move
- Land softly and quietly

7. Side Plank 2

INSTRUCTION: Begin by lying on your side with the elbow of your bottom arm directly under your shoulder. Place your top foot directly on top of your bottom foot and your top hand on your hip. Push down through your forearm and feet and lift your body from the floor. Raise your top arm vertically once you reach the raised position. Hold this position for the allotted time and then repeat on the opposite side.

CUES:

- Keep your head in line with your body
- Brace your body as you would against the wind or a wave in the ocean
- Squeeze your butt
- Form a perfectly straight line with your body from your head to your feet

Ages 16-17: Exercise instructions and cues

1. Carioca

INSTRUCTION: Move sideways with alternating steps of your trailing foot in front of and behind your lead foot. Repeat by moving in the opposite direction.

CUES:

- Keep your head in line with your body as you move
- Brace the middle of your body as you would against the wind or a wave in the ocean
- Hips, knees and toes point straight ahead as you move

2. Angled Run - Forward & Backward

INSTRUCTION: Begin by running forward to a cone or marker at an angle to your right. Quickly change direction and then run backward to the next cone on an angle to your right. Repeat this activity…

CUES:

- Stand up tall as you run keeping your head in line with your body
- Hips, knees and toes point straight ahead as you run
- See the field/court from as high as possible

3. Lunge 3

INSTRUCTION: Begin by standing in an upright position with your hands held in front of your body and feet at shoulder width. Step forward with one foot and lower your opposite knee toward the floor. Slowly return to the starting position and then step sideways with the same foot and lower your body by bending your hip and knee. Finally, step backward with the same foot and lower your knee toward the floor. Repeat this activity with the opposite leg.

CUES:

- Keep your head in line with your body
- Brace your body as you would against the wind or a wave in the ocean
- Hip, knee and ankle joints stacked on top of each other as you move

4. Double Leg Squat 2

INSTRUCTION: Begin by in a standing upright position with your hands held behind your head and feet at shoulder width. Squat by bending at your knees and hips until your knees are close to a 90 degree angle. Slowly return to the starting position and repeat this movement for the allotted time.

CUES:

- Keep your head in line with your body

- Brace your body as you would against the wind or a wave in the ocean
- Hip, knee and ankle joints stacked on top of each other as you move
- Open (break) a glass door with your butt

5. Broad Jump 2

INSTRUCTION: Begin by standing in an upright position with your arms at your sides and elbows bent. Quickly swing both arms backward and then forward as you jump forward, landing with both legs at the same time. Quickly repeat this movement for the allotted time.

CUES:

- Keep your head in line with your body
- Brace your body as you would against the wind or a wave in the ocean
- Hip, knee and ankle joints stacked on top of each other as you move
- Land softly and quietly
- Open (break) a glass door with your butt when you land

6. Scissor Jumps 3

INSTRUCTION: Begin in a lunge position with your hands placed behind your head and your feet in line with each other (as if on a balance beam). Jump vertically into the air and switch your front foot to the back and your back foot to the front. Return to a lunge position after you land. Repeat this movement for the allotted time.

CUES:

- Keep your head in line with your body
- Brace your body as you would against the wind or a wave in the ocean
- Hip, knee and ankle joints stacked on top of each other as you move
- Land softly and quietly

7. Side Plank 3

INSTRUCTION: Begin by lying on your side with the elbow of your bottom arm directly under your shoulder. Place your top foot directly on top of your bottom foot and your top hand on your hip. Push down through your forearm and feet and lift your body from the floor. Raise your top arm and top leg vertically once you reach the raised position. Hold this position for the allotted time and then repeat on the opposite side.

CUES:

- Keep your head in line with your body
- Brace your body as you would against the wind or a wave in the ocean
- Squeeze your butt

- Form a perfectly straight line with your body from your head to your feet

Appendix 2. Proportion of participants ages 8-11 years who performed exercises correctly with proper alignment

Exercise		8-9 years	10-11 years	p-value*
Forward/Backward Jog	Exercise instruction	28.2	38.3	0.17
	Technique cues	62.0	78.7	0.02
Figure 8 Run (narrow)	Exercise instruction	36.6	58.5	0.005
	Technique cues	63.4	92.6	<0.001
Level 1 Lunge	Exercise instruction	4.2	6.4	0.73
	Technique cues	19.7	33.0	0.06
Level 1 Double Leg Squat	Exercise instruction	18.3	19.2	0.89
	Technique cues	39.4	48.9	0.22
Level 1 Broad Jump	Exercise instruction	11.3	10.6	0.90
	Technique cues	16.9	25.5	0.18
Level 1 Scissor Jump	Exercise instruction	2.8	3.2	1.00
	Technique cues	4.2	9.6	0.19
Level 1 Side Plank	Exercise instruction	22.5	27.7	0.45
	Technique cues	56.3	62.8	0.40

*p-values represent the comparison between the two age groups

Appendix 3. Proportion of participants ages 12-15 years who performed exercise correctly with proper alignment

Exercise		12-13 years	14-15 years	p-value*
Side Shuffle	Exercise instruction	41.8	45.6	0.66
	Technique cues	83.5	73.7	0.16
Figure 8 Run (wide)	Exercise instruction	44.3	38.6	0.51
	Technique cues	83.5	71.9	0.10
Level 2 Lunge	Exercise instruction	10.1	12.3	0.69
	Technique cues	36.7	31.6	0.54
Level 2 Double Leg Squat	Exercise instruction	36.7	38.6	0.82
	Technique cues	68.4	64.9	0.67
Level 2 Broad Jump	Exercise instruction	11.4	14.0	0.65
	Technique cues	43.0	49.1	0.48
Level 2 Scissor Jump	Exercise instruction	3.8	15.8	0.02
	Technique cues	24.1	28.1	0.60
Level 2 Side Plank	Exercise instruction	41.8	52.6	0.21
	Technique cues	81.0	77.2	0.59

*p-values represent the comparison between the two age groups

Appendix 1

Ages 8-11: Exercise instructions and cues

1. Jogging - Forward & Backward

INSTRUCTION: Slowly jog forward and backward.

CUES:

- Stand up tall as you run keeping your head in line with your body
- Hips, knees and toes point straight ahead as you run
- See the field/court from as high as possible

2. Figure 8 Run - Narrow

INSTRUCTION: Run in a figure 8 motion through a series of cones or markers.

CUES:

- Stand up tall as you run keeping your head in line with your body
- Hips, knees and toes point straight ahead as you run
- See the field/court from as high as possible

3. Lunge 1

INSTRUCTION: Stand in an upright position with your hands held in front of your body and feet at shoulder width. Step forward with one foot and lower your opposite knee toward the floor. Slowly return to the starting position and repeat this activity with the opposite leg.

CUES:

- Keep your head in line with your body
- Brace your body as you would against the wind or a wave in the ocean
- Hip, knee and ankle joints stacked on top of each other as you move

4. Double Leg Squat 1

INSTRUCTION: Stand in an upright position with your hands held in front of your body and feet at shoulder width. Lower your body by bending at your hips and knees until your knees are close to a 90 degree angle. Slowly return to the starting position.

CUES:

- Keep your head in line with your body
- Brace your body as you would against the wind or a wave in the ocean
- Hip, knee and ankle joints stacked on top of each other as you move

- Open (break) a glass door with your butt

5. Broad Jumps 1

INSTRUCTION: Stand in an upright position with your arms at your sides and elbows bent. Quickly swing both arms backward and then forward as you jump, landing with both legs at the same time. Pause briefly before jumping again.

CUES:

- Keep your head in line with your body
- Brace your body as you would against the wind or a wave in the ocean
- Hip, knee and ankle joints stacked on top of each other as you move
- Land softly and quietly
- Open (break) a glass door with your butt when you land

6. Scissor Jumps 1

INSTRUCTION: Stand with one foot in front of the other with your arms at your sides and elbows bent. Jump up and switch your front foot to the back and your back foot to the front. Repeat this movement with the opposite legs.

CUES:

- Keep your head in line with your body
- Brace your body as you would against the wind or a wave in the ocean
- Hip, knee and ankle joints stacked on top of each other as you move
- Land softly and quietly

7. Side Plank 1

INSTRUCTION: Lie on your side with the elbow of your bottom arm directly under your shoulder. Stack your feet and put your top hand on your hip. Push down through your forearm and feet and lift your body from the floor.

CUES:

- Keep your head in line with your body
- Brace your body as you would against the wind or a wave in the ocean
- Squeeze your butt
- Form a perfectly straight line with your body from your head to your feet

Ages 12-15: Exercise instructions and cues

1. Side Shuffle

INSTRUCTION: Begin in an athletic stance or ready position and then shuffle feet laterally while repeatedly raising arms overhead.

CUES:

- Keep your head in line with your body as you move
- Brace your body as you would against the wind or a wave in the ocean
- Hips, knees and toes point straight ahead as you move

2. Figure 8 Run - Wide

INSTRUCTION: Run in a figure 8 motion through a series of cones or markers.

CUES:

- Stand up tall as you run keeping your head in line with your body
- Hips, knees and toes point straight ahead as you run
- See the field/court from as high as possible

3. Lunge 2

INSTRUCTION: Begin by standing in an upright position with your hands held in front of your body and feet at shoulder width. Step forward with one foot and lower your opposite knee toward the floor. Slowly return to the starting position and then step backward with the same foot and lower your knee toward the floor. Repeat this activity with the opposite leg.

CUES:

- Keep your head in line with your body
- Brace your body as you would against the wind or a wave in the ocean
- Hip, knee and ankle joints stacked on top of each other as you move

4. Double Leg Squat 2

INSTRUCTION: Begin by in a standing upright position with your hands held behind your head and feet at shoulder width. Squat by bending at your knees and hips until your knees are close to a 90 degree angle. Slowly return to the starting position and repeat this movement for the allotted time.

CUES:

- Keep your head in line with your body
- Brace your body as you would against the wind or a wave in the ocean
- Hip, knee and ankle joints stacked on top of each other as you move

- Open (break) a glass door with your butt

5. Broad Jump 2

INSTRUCTION: Begin by standing in an upright position with your arms at your sides and elbows bent. Quickly swing both arms backward and then forward as you jump forward, landing with both legs at the same time. Quickly repeat this movement for the allotted time.

CUES:

- Keep your head in line with your body
- Brace your body as you would against the wind or a wave in the ocean
- Hip, knee and ankle joints stacked on top of each other as you move
- Land softly and quietly
- Open (break) a glass door with your butt when you land

6. Scissor Jump 2

INSTRUCTION: Begin in a lunge position with your hands placed behind your head. Jump vertically into the air and switch your front foot to the back and your back foot to the front. Return to a lunge position after you land. Repeat this movement for the allotted time.

CUES:

- Keep your head in line with your body
- Brace your body as you would against the wind or a wave in the ocean
- Hip, knee and ankle joints stacked on top of each other as you move
- Land softly and quietly

7. Side Plank 2

INSTRUCTION: Begin by lying on your side with the elbow of your bottom arm directly under your shoulder. Place your top foot directly on top of your bottom foot and your top hand on your hip. Push down through your forearm and feet and lift your body from the floor. Raise your top arm vertically once you reach the raised position. Hold this position for the allotted time and then repeat on the opposite side.

CUES:

- Keep your head in line with your body
- Brace your body as you would against the wind or a wave in the ocean
- Squeeze your butt
- Form a perfectly straight line with your body from your head to your feet

Ages 16-17: Exercise instructions and cues

1. Carioca

INSTRUCTION: Move sideways with alternating steps of your trailing foot in front of and behind your lead foot. Repeat by moving in the opposite direction.

CUES:

- Keep your head in line with your body as you move
- Brace the middle of your body as you would against the wind or a wave in the ocean
- Hips, knees and toes point straight ahead as you move

2. Angled Run - Forward & Backward

INSTRUCTION: Begin by running forward to a cone or marker at an angle to your right. Quickly change direction and then run backward to the next cone on an angle to your right. Repeat this activity…

CUES:

- Stand up tall as you run keeping your head in line with your body
- Hips, knees and toes point straight ahead as you run
- See the field/court from as high as possible

3. Lunge 3

INSTRUCTION: Begin by standing in an upright position with your hands held in front of your body and feet at shoulder width. Step forward with one foot and lower your opposite knee toward the floor. Slowly return to the starting position and then step sideways with the same foot and lower your body by bending your hip and knee. Finally, step backward with the same foot and lower your knee toward the floor. Repeat this activity with the opposite leg.

CUES:

- Keep your head in line with your body
- Brace your body as you would against the wind or a wave in the ocean
- Hip, knee and ankle joints stacked on top of each other as you move

4. Double Leg Squat 2

INSTRUCTION: Begin by in a standing upright position with your hands held behind your head and feet at shoulder width. Squat by bending at your knees and hips until your knees are close to a 90 degree angle. Slowly return to the starting position and repeat this movement for the allotted time.

CUES:

- Keep your head in line with your body

- Brace your body as you would against the wind or a wave in the ocean
- Hip, knee and ankle joints stacked on top of each other as you move
- Open (break) a glass door with your butt

5. Broad Jump 2

INSTRUCTION: Begin by standing in an upright position with your arms at your sides and elbows bent. Quickly swing both arms backward and then forward as you jump forward, landing with both legs at the same time. Quickly repeat this movement for the allotted time.

CUES:

- Keep your head in line with your body
- Brace your body as you would against the wind or a wave in the ocean
- Hip, knee and ankle joints stacked on top of each other as you move
- Land softly and quietly
- Open (break) a glass door with your butt when you land

6. Scissor Jumps 3

INSTRUCTION: Begin in a lunge position with your hands placed behind your head and your feet in line with each other (as if on a balance beam). Jump vertically into the air and switch your front foot to the back and your back foot to the front. Return to a lunge position after you land. Repeat this movement for the allotted time.

CUES:

- Keep your head in line with your body
- Brace your body as you would against the wind or a wave in the ocean
- Hip, knee and ankle joints stacked on top of each other as you move
- Land softly and quietly

7. Side Plank 3

INSTRUCTION: Begin by lying on your side with the elbow of your bottom arm directly under your shoulder. Place your top foot directly on top of your bottom foot and your top hand on your hip. Push down through your forearm and feet and lift your body from the floor. Raise your top arm and top leg vertically once you reach the raised position. Hold this position for the allotted time and then repeat on the opposite side.

CUES:

- Keep your head in line with your body
- Brace your body as you would against the wind or a wave in the ocean
- Squeeze your butt

- Form a perfectly straight line with your body from your head to your feet

Appendix 2. Proportion of participants ages 8-11 years who performed exercises correctly with proper alignment

Exercise		8-9 years	10-11 years	p-value*
Forward/Backward Jog	Exercise instruction	28.2	38.3	0.17
	Technique cues	62.0	78.7	0.02
Figure 8 Run (narrow)	Exercise instruction	36.6	58.5	0.005
	Technique cues	63.4	92.6	<0.001
Level 1 Lunge	Exercise instruction	4.2	6.4	0.73
	Technique cues	19.7	33.0	0.06
Level 1 Double Leg Squat	Exercise instruction	18.3	19.2	0.89
	Technique cues	39.4	48.9	0.22
Level 1 Broad Jump	Exercise instruction	11.3	10.6	0.90
	Technique cues	16.9	25.5	0.18
Level 1 Scissor Jump	Exercise instruction	2.8	3.2	1.00
	Technique cues	4.2	9.6	0.19
Level 1 Side Plank	Exercise instruction	22.5	27.7	0.45
	Technique cues	56.3	62.8	0.40

*p-values represent the comparison between the two age groups

Appendix 3. Proportion of participants ages 12-15 years who performed exercise correctly with proper alignment

Exercise		12-13 years	14-15 years	p-value*
Side Shuffle	Exercise instruction	41.8	45.6	0.66
	Technique cues	83.5	73.7	0.16
Figure 8 Run (wide)	Exercise instruction	44.3	38.6	0.51
	Technique cues	83.5	71.9	0.10
Level 2 Lunge	Exercise instruction	10.1	12.3	0.69
	Technique cues	36.7	31.6	0.54
Level 2 Double Leg Squat	Exercise instruction	36.7	38.6	0.82
	Technique cues	68.4	64.9	0.67
Level 2 Broad Jump	Exercise instruction	11.4	14.0	0.65
	Technique cues	43.0	49.1	0.48
Level 2 Scissor Jump	Exercise instruction	3.8	15.8	0.02
	Technique cues	24.1	28.1	0.60
Level 2 Side Plank	Exercise instruction	41.8	52.6	0.21
	Technique cues	81.0	77.2	0.59

*p-values represent the comparison between the two age groups