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The efficacy of injury prevention training is greater in
high risk compared to low risk elite female youth soccer
players

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Abstract

Background: The efficacy of robustness training on high versus low risk individuals within high risk groups is currently unknown.

Hypothesis/Purpose: The purpose of this study was to explore the efficacy of robustness training on injury risk factors in female youth soccer players and examine if high risk individuals are greater responders to such training

Study design: Controlled laboratory study

Methods: 125 elite youth female footballers on the English FA talent pathway were randomly selected into a training (n = 71) or control group (n = 54). Relative leg stiffness, 2D knee valgus and knee flexion range of motion (ROM) from a single leg counter-movement jump and probability of high knee abduction moment (pKAM) risk were all determined before and after a 16 week robustness training programme. For further analysis participants in the training group were split into high (pKAM >0.80; n = 33) and low risk (pKAM <0.55; n = 33) groups. Magnitude based inferences (MBI) were used to explore differences between the control and intervention and the high and low risk groups.

Results: MBI demonstrated significant beneficial effects in the training group for knee valgus, pKAM and leg stiffness compared with the control group. The control group demonstrated possible worthwhile differences in knee flexion ROM compared to the intervention group. The high risk group demonstrated likely/very likely worthwhile differences compared to the low risk group for all parameters.

Conclusion: Robustness training induces significant beneficial improvements in injury risk factors in female youth soccer players. The beneficial effects of this multi-dimensional program are greater in those individuals who are classified as high risk.

Keywords: injury risk, robustness training, youth, female

What is known about the subject?

Previous studies have demonstrated that puberty is a high risk period for injury incidence and that females are at greater risk of injury than males. Intervention programs have been shown to be effective for older youth females however our understanding of whether multi-dimensional training is more effective for high risk individuals is limited.

What this study adds to existing knowledge:

The majority of previous studies on injury prevention in youth female athletes has focused on those post peak height velocity when risk is lower (. To our knowledge this is the first study to identify significant reduction in risk factors in younger aged females (11-16y) going through puberty. Our study also identifies for the first time that an increase in knee valgus risk through normal growth and maturation is evident, reinforcing the need to intervention programs in this group. Importantly we show that high risk individuals (greater probability of pKAM) within high risk groups gain greater benefits from injury prevention programs high-lighting that both screening and individualizing training is important.

Introduction

It is well recognised that based on hours of exposure to sporting activity females are more likely to suffer a non-contact anterior cruciate ligament (ACL) injury compared to males^{1,11,12,13,14} with the proposed mechanisms for this increased incidence rate being multifactorial. The high-intensity actions performed during soccer, especially jumping and landing tasks, often result in injury risk, especially where individual growth and maturation may predispose youth players to a higher risk^{3,10,13,20,22,36}. Epidemiology studies have reported that the frequency and severity of injuries among youth athletes accelerate and peak around peak height velocity (PHV), when rapid disproportional growth is evident^{34,35}. Data have also identified that early single sport specialisation increases injury incidence in 7-18y old athletes¹⁹. It would appear that single sport specialised youth athletes, on elite pathways, who are going through maturation, can be classified as high injury risk groups. Additionally due to the association between greater probability of high knee abduction moments (pKAM) on landing and knee joint loading^{28,29}, individuals with high pKAM can be considered high risk for joint injuries.

A number of recent systematic reviews and meta-analyses have demonstrated the preventative effect of neuromuscular training in reducing the incidence of lower limb injury in youth athletes, and that these effects are greater for females compared to males^{2,8,9,32}. Intervention programs that include components of strengthening, proximal control exercises, landing mechanics training and multi-exercise genres have all been shown to reduce injury incidence in young female athletes²⁵. Two recent studies have also shown the efficacy of the FIFA11+Kids in boys aged 8-13y-old, with a 48% reduction in injury incidence³³ and significant improvements in hip range of motion and dynamic postural control in 12y-olds³¹. Available data consistently indicates that these programmes are only effective when high

compliance rates are maintained^{2,15,33}. However, there are also limitations in the evidence base that include: lack of data on children under 14 years of age; individuals that have not been identified as high risk; compliance and behaviour change have not been determined.

Despite there being a range of prevention programs available there appears to be only a couple of studies that have shown that youth female athletes identified as high risk exhibit greater improvements in knee abduction moment on landing²⁶ and in kinematics following a program specifically targeted on movement biomechanics, compared to those identified as low risk¹⁵. It is therefore important to explore if a multi-component intervention programme is more beneficial for high risk compared to low risk individuals within high risk groups, for a range of injury risk factors. Thus, the purpose of this study was to examine the efficacy of a robustness training programme in a high risk group (elite female youth single sport specialists) and to explore if such a programme is more beneficial for high risk individuals (high pKAM) in terms of injury risk. Specifically we hypothesised that a robustness training programme would result in reduced knee valgus, reduced pKAM and increased leg stiffness, and that these improvements would be greater in those individuals identified as high risk.

Materials and Methods

This was a repeated measures, cluster randomized control trial. Two hundred and twelve female youth footballers from three age groups (U12, U14 and U16y), who were attending five of the FA South West Advanced Coaching Centers (ACC) (English FA girl's talent pathway) were invited to participate in this study. We used the "lottery method" for cluster randomisation of ACCs into a control or intervention group. A blinded researcher, who was not involved in any aspect of the study, conducted the randomization. Three Centers were randomly selected as an intervention group and 2 Centers as a control group. Only participants where a full data set was collected pre and post the intervention, and those who completed at least 80% of the training, were included in the final analysis. This provided a final sample size of $n = 125$ with the

intervention group consisting of $n = 71$ (age, $13.1 \pm 1.7y$; stature $155.6 \pm 9.0cm$; body mass $49.5 \pm 10.0kg$; maturity offset $-0.81 \pm 1.16y$; tibial length $35.5 \pm 2.5cm$) and the control group $n = 54$ (age, $12.8 \pm 1.6y$; stature $154.4 \pm 8.9cm$; body mass $51.4 \pm 9.6kg$; maturity offset $-1.01 \pm 1.11y$; tibial length $36.3 \pm 2.3cm$) girls. The intervention group was split into high (pKAM >0.80 ; $n = 33$) and low (pKAM <0.55 ; $n = 33$) risk groups based on their pre intervention pKAM data. This resulted in five participants being removed from the analysis due to them falling within the pKAM range of 0.55-0.80.

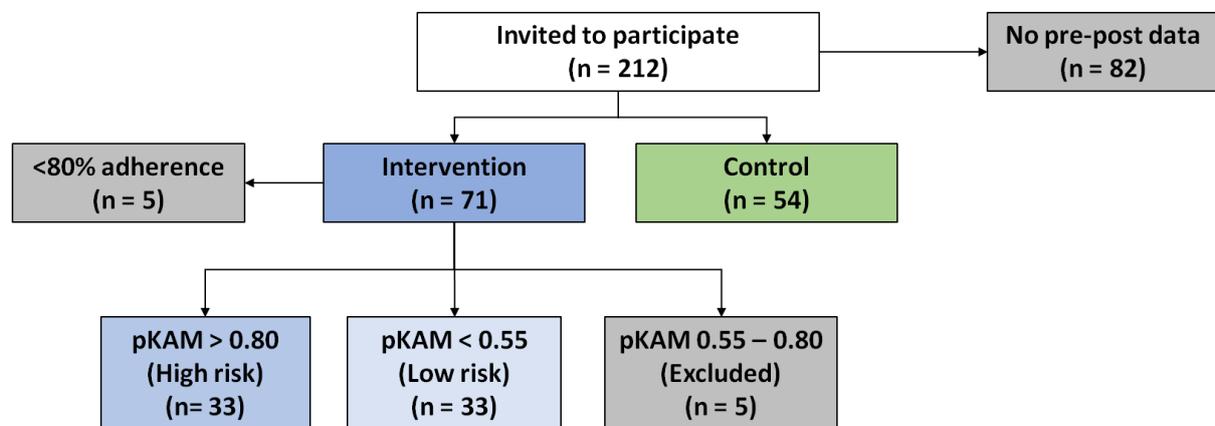


Figure 1: Flow diagram of participant recruitment, randomisation and inclusion in final analysis

Participants were instructed not to take part in any vigorous physical activity 48 hrs preceding each testing day. None of the participants were participating in any form of systematic injury prevention training or reported any form of musculoskeletal disorder at the time of testing. The participants were provided with both verbal and written information regarding the study procedures before testing and written consent was obtained from both parents and players and additionally assent from the players. The study was approved by the University's Research Ethics Committee. Anthropometric data were collected using standard procedures and maturity offset was determined using the equation of Mirwald et al.²³

Intervention Program

Leg stiffness, knee valgus, knee flexion range of motion and pKAM were all determined before and after a 16-week intervention period. The robustness training was initially delivered and monitored by a physical performance coach who had more than 10 years of experience of working with youth soccer populations. Training was also delivered to the soccer coaches on how to instruct and lead the players through both the warm up and robustness routines. All subsequent sessions were led by the soccer coach but the physical performance coach was responsible for progressing players throughout the duration of the study. The coaches were supplemented with written instructions, hand-outs and materials to ensure sessions were correctly performed. The 3 training sessions per week consisted of 1 coach led session and 2 player led sessions. The 20 minute coach led session was delivered as part of a soccer specific warm up, and consisted of four main components that included: 1) Dynamic warm up; 2) Dynamic flexibility; 3) Plyometric and landing technique; 4) Speed and agility (Table 1). The player led session labelled 'robustness' (Table 2) was taught to players by the physical performance coach, was performed on 2 days per week within the participants own time, and adherence monitored using weekly activity diaries (see online supplement for full pictorial description of all exercises). Correct performance of the exercises was monitored by the physical performance coach throughout the intervention period, and adjusted where necessary. The robustness session included body weight, lower extremity and trunk strength, stabilisation and balance exercises aimed to target the posterior chain (glutes and hamstrings), hip abductors, and core musculature. This session was performed as a circuit with 2 min rest after all exercises had been completed once.

Table 1. Warm up session with component, exercise and repetition

Component	Exercise	Repetitions
Dynamic warm up	Jog forward	20m
	Jog backwards	20m
	Low level skip	20m
	High knees out and back	20m
	Side step out and back	20m
	Carioca out and back	20m
	Cross step out and back	15m
	Rotating side step	20m
Dynamic flexibility	L1 Static crawls; L2 Spiderman crawls	8es
	Inchworm	6
	L1 Static lunge; L2 Walking lunges	10es
	Walking quadriceps stretch	4es
	Lateral lunge	10es
	Hamstring starter stretch	10es
	L1 Arabesque double leg; L2 Split stance; L3 Single leg	8es
	Nordic hamstrings	6
	Quick-fire hamstrings	10es
	Plyometrics	Pogos
Ankling		10m
L1 Squat jumps; L2 Countermovement jumps; L3 Tuck jumps		8
Alternate step and hold		6es
L1 SL Hop and hold; L2 SL repeated hops		6es

Speed / COD	5m to 3 step deceleration	4
	10m, stop, back pedal 5m	3
	15m, back pedal 5m, sprint 10m and decelerate	1
	10m, side step, 10m	1es
	5m side step out and back to 10m sprint	1es
	10m, diagonal cut step, 10m	1es

Note: L1: level 1 exercise followed by progression to L2: level 2 exercise followed by L3: level 3 exercise when subject is able to achieve technical and physical competency; COD=change of direction; SL=single leg; m=metres; es= each side.

Table 2. Robustness session exercises with instruction, sets and reps/time

Exercise	Instruction	Sets	Reps/ Time
Glute wall holds	Reach head to ceiling stretching body upwards. Push wall away from you with knee (keeping hips facing forwards). Push out slightly with standing leg as if pushing carpet away from you.	2	20-60s
Clams	Start with Shoulders, Hips & Ankles in straight line. Lift top knee slowly keeping ankles fixed together. Keep hand on hip/ lower back to avoid any additional movement.	2	12es
Box Squat	Sit back to a seat - hips before knees. "Show Your Badge" ensure mirror or partner can see what's on your shirt. "Separate the floor" push feet outwards gently.	2	10-25
SL high knee balance	Reach up to ceiling stretching body tall. Keep hips level, slowly lift knee to parallel to floor and return without touching. Feel strong.	2	10-30s
Static lunge	Sit down through the middle of your feet. Stand tall and strong. Drive the floor away from you with front leg to return.	2	10-20

Supine glute bridge	Squeeze glutes and lift hips from floor to level with shoulders and knees. Push down into floor with feet. Keep hips level and strong.	2	12-30
Nordic hamstring	Stay tall throughout movement. Keep distance between top of hips and bottom of ribs the same. Lower to maximal range, falling to floor when no longer in control of the movement.	2	4-10
Side plank	Push down into floor with elbow, lifting shoulders to ceiling. Keep head, shoulders, hips and knees in a straight line without rotating. Be as tall as possible.	2	30-60s
SL Y balance	Reach out in each direction as far as possible. Bend at knee and hip to get as low as possible for each rep. Try not to put your foot down, gently touch floor at maximal reach.	2	3-6es
Front plank	Push through floor with elbows, lifting shoulders. Keep hips in line with shoulders and knees, don't allow to sag. Be as tall as possible.	2	30-60s

NB. SL=single leg; s= seconds; es= each side.

The participants in both the intervention and control group did not perform any additional training which focused on strength and conditioning or movement competency. The control group undertook their normal warm up routine during the training session and had no individual prescribed player led intervention.

Leg Stiffness

Leg stiffness was calculated from contact time data obtained during a sub-maximal hopping protocol and a coefficient of variation for female youths has been reported to be 8.2%⁷. In the current study, the procedures were repeated twice and an average stiffness value reported. This method improves the reliability by a factor of $1/\sqrt{2}$, giving an adjusted coefficient of variation

of 7.2%. For each trial, participants were instructed to perform 20 consecutive hops on a mobile contact mat (Smartjump, Fusion Sport, Australia) at a frequency of 2.5 Hz, with data collected instantaneously via a hand-held unit (iPAQ, Hewlett Packard, USA). Hopping frequency was maintained via an audio signal from a quartz metronome (SQ-44, Seiko, UK). Participants were instructed to: a) keep hands on the hips at all times to avoid upper body interference; b) jump and land on the same spot; c) land with legs fully extended and to look forward at a fixed position to aid balance⁶. Absolute leg stiffness ($\text{kN}\cdot\text{m}^{-1}$) was calculated using the equation proposed by Dalleau et al.⁶, and relative leg stiffness was determined by dividing absolute leg stiffness by body mass and limb length to provide a dimensionless value⁷.

Kinematic Analysis

Two-dimensional frontal and sagittal plane knee kinematic data were captured using high speed video cameras (Quintic) during a single leg countermovement jump (SL CMJ). Cameras were positioned 2m from the capture area to reduce potential perspective errors, and were focused and zoomed towards the capture location. Participants stood 2 steps behind a landing mat and were instructed to perform a SL CMJ off their dominant leg following a 2 step run up, aiming to then land on both feet on the landing mat. This jump-landing sequence has previously been referred to as a vertical stop jump task^{4,5}. Participants were instructed to perform the SL CMJ aiming to jump maximally to replicate heading a football. This jump landing task is suggested to have more sports specificity, replicating a soccer specific action, compared to previous methodology where participants performed a drop jump task off a box^{4,5}. Prior to testing participants were allowed to familiarise themselves with the SL CMJ landing, performing three practice trials. Once participants were able to perform the jump-landing sequence they performed three test trials, feedback between trials was provided ensuring participants jumped

maximally in all trials. 2D valgus and knee flexion ROM was determined from each trail and the greatest value used in subsequent analysis.

Frontal and sagittal videos were imported into the Quintic biomechanics software (V26) package to measure both knee valgus motion and knee flexion range of motion. Initial video calibration for the x-axis was achieved using the known distance of the landing mat. The knee valgus motion was calculated using the frontal view by drawing a line on the knee joint centre at the frame prior to initial contact (L_1) and at a maximum medial position (L_2). With the displacement measured between the two lines representative of knee valgus motion during the SL CMJ landing task. Using the sagittal view knee flexion angles were measured at the frame prior to initial contact and at maximum knee flexion from the greater trochanter, lateral knee joint line, and lateral malleolus. The knee flexion range of motion was defined as the difference between the angles ($\Theta_2 - \Theta_1$) prior to initial contact and maximum knee flexion.

Knee abduction moment

An ACL injury predictive algorithm developed by Myer et al.²⁹ was used to determine the probability of high knee abduction moment (pKAM) risk during the SL CMJ task. The algorithm has previously been reported to have high sensitivity (84%) and specificity (67%) being able to identify female athletes who demonstrate a high pKAM, increasing the risk of ACL injury²⁹. The algorithm includes five predictive variables that include tibia length, knee valgus motion, knee flexion range of motion, body mass and quadriceps to hamstrings (Q:H) ratio that collectively predict the probability of high knee abduction moment (pKAM) whilst landing. A surrogate measure of Q:H strength ratio was used, that has previously been defined using a linear regression analysis to predict Q:H ratio based on the participants' body mass²⁹. The Q:H strength ratio was obtained by multiplying the subject's body mass by 0.01 and adding the resultant value to 1.10. Using the five variables the tibia length, body mass, QH ratio, knee

valgus, and knee flexion range of motion, the ACL injury predictive algorithm was used to obtain pKAM. Using the algorithm, a vertical edge was drawn from the axis of each of the five variables to the points axis. All the recorded points were then summed and located on the total points line with a vertical edge drawn down to the probability line, identifying the probability the participant will demonstrate a high pKAM (>21.74 Nm) whilst landing.

Statistical analysis

Statistical analyses were performed using SPSS (v22.0). The distribution of raw data sets was checked for homogeneity and skewness using the Kolmogorov-Smirnov test. Descriptive statistics including means and standard deviation were calculated for each measure. Independent sample t-tests were run to evaluate baseline differences between the groups (training vs. control) for each dependent variable.

Magnitude-based inference analysis for the intervention and control groups were estimated via Student t-test with unequal-variances computed for change scores between paired sessions (intervention vs control) at each test occasion (pre-test [baseline], post-test) for each variable. Alpha was set at $p < 0.05$. Each participant's change score between pre and post-tests was expressed as a percentage of the baseline value via analysis of log-transformed values, to reduce bias arising from non-uniformity of error. This approach of data analysis uses confidence intervals to calculate the probability that a difference is of practical relevance or trivial when a value for the smallest worthwhile change is entered. A difference score of at least 0.2 of the between-participant standard deviation (representing a small effect) was considered to be practically worthwhile¹⁷. The qualitative descriptors proposed by Hopkins¹⁸ were used to interpret the probabilities that the true effects are harmful, trivial or beneficial: <1%, almost certainly not; 1–4%, very unlikely; 5–24%, unlikely or probably not; 25–74%, possibly or may be; 75–94%, likely or probably; 95–99%, very likely; >99%, almost certainly.

This spreadsheet also provides estimates of the effect of an intervention adjusted to any chosen value of the covariate, thereby reducing the possibility for confounding of the effect when a characteristic is unequal in the experimental and control groups: Thus, the baseline pre-test value of each dependent variable was included to avoid the phenomenon of regression to the mean and thereby allowing for a more accurate estimation of the effects of the robustness intervention in comparison with the control group. The level of significance was set at $P \leq 0.05$ for all tests.

Results

There were no statistically significant difference in maturity status (maturity offset), age, stature, body mass or tibial length between the training and control groups prior to testing. Mean pKAM for the low risk group was 0.35 ± 0.14 and 0.87 ± 0.08 for the high risk group. Pre and post intervention data for both the control and intervention groups as well as absolute differences for all outcome variables can be seen in table 3 below.

Table 3: Pre and post-tests (Control and Intervention) for physical performance outcomes (mean \pm standard deviation [SD]). The absolute mean difference between pre and post-test are also reported.

Physical performance measure	Control						Intervention					
	Pre-test		Post-test		Difference		Pre-test		Post-test		Difference	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Knee flexion range of motion (°)	43.5	± 8.4	49.1	± 10.1	5.6	± 9.3	45.9	± 11.7	47.7	± 10.9	1.8	± 11.6
Knee valgus motion (°)	4.3	± 1.9	4.7	± 1.9	0.4	± 2.3	5.4	± 2.4	2.7	± 1.7	-2.7	± 2.6
pKAM	0.58	± 0.24	0.58	± 0.24	0.00	± 0.22	0.61	± 0.27	0.53	± 0.23	-0.08	± 0.21
Leg stiffness	25.7	± 4.9	29.4	± 7.9	3.7	± 6.4	26.9	± 4.6	34.3	± 8.9	7.4	± 9.6

Smaller values are advantageous for knee valgus motion and pKAM; Greater values are advantageous for knee flexion range of motion and leg stiffness

Magnitude based inferences data indicated that there were possibly worthwhile differences for knee flexion ROM and pKAM between the intervention and control groups. For leg stiffness there were likely worthwhile differences and for knee valgus very likely worthwhile differences between the intervention and control groups. These differences demonstrated beneficial effects for all parameters for the intervention group compared with the control group except for knee flexion ROM. These data can be seen in table 4 and Figure 2 respectively.

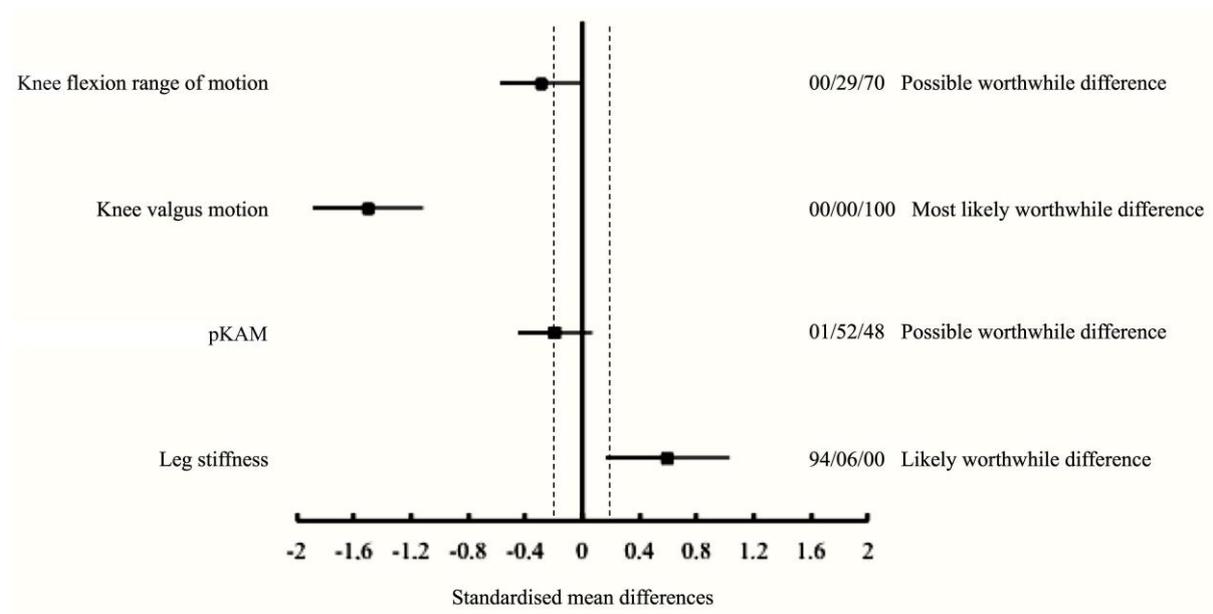


Figure 2: Differences between intervention and control groups based on standardised mean differences (positive/trivial/negative)

Table 4: Knee flexion range of motion, knee valgus, pKAM and leg stiffness mean percentage change between control and intervention group. Confidence limits (CL), chances that the true effects were substantial, and practical assessments of the effects are shown.

Paired comparison	Mean Change (%)	±90% CL	Effect Size (d)	Chances that the true effects were substantial ^a (%)...			
				Positive	Trivial	Negative	Qualitative inference ^b
Knee flexion range of motion	- 7.0	-13.3 to -0.2	-0.29	0	29	70	Possibly worthwhile differences
Knee valgus motion	-55.2	-63.6 to -44.9	-1.5	0	0	100	Most likely worthwhile differences
pKAM	-10.1	-22 to 3.7	-0.19	1	52	48	Possibly worthwhile differences
Leg stiffness	11.4	3.2 to 20.2	0.60	94	6	0	Likely worthwhile differences

± 90% CL: add and subtract this number to the mean effect to obtain the 90% confidence limits for the true difference.

^a Substantial is an absolute change in performance of 0.2 standardised Cohen's units (see Methods).

^b If chance of benefit and harm both >5%, true effect was assessed as unclear (could be beneficial or harmful). Otherwise, chances of benefit or harm were assessed as follows: <1%, almost certainly not; 1-5%, very unlikely; > 5-25%, unlikely; >25-75%, possible; >75-95%, likely; >95-99%, very likely; >99%, almost certain.

Pre and post intervention mean data for both the high and low risk groups as well as absolute differences for all outcome variables can be seen in table 5 below.

Magnitude based inferences data indicated that there were likely worthwhile differences for knee flexion ROM, leg stiffness and knee valgus between the high and low risk groups. For pKAM there were very likely worthwhile differences between the high and low risk groups. These differences demonstrated beneficial effects for all parameters for the high risk group compared with the low risk group. These data can be seen in table 6 and Figure 3 respectively.

Table 5: Low and high risk pre and post-test results (mean \pm standard deviation [SD]) for all outcomes. The absolute mean differences between pre and post-test are also reported.

Physical performance measure	Low Risk						High risk					
	Pre-test		Post-test		Difference		Pre-test		Post-test		Difference	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Knee flexion range of motion (°)	47.6	± 9.2	46.8	± 9.1	-0.8	± 9.4	45.8	± 13.4	49.6	± 12.1	3.9	± 13.4
Knee valgus motion (°)	3.9	± 1.6	2.5	± 1.7	-1.4	± 1.9	6.9	± 2.2	2.9	± 1.8	-4.0	± 2.6
pKAM	0.35	± 0.14	0.38	± 0.17	0.03	± 0.17	0.87	± 0.08	0.67	± 0.2	-0.20	± 0.19
Leg stiffness	28.3	± 5.2	34.0	± 8.3	5.7	± 9.3	25.2	± 3.4	34.2	± 10.0	8.9	± 10.3

Smaller values are advantageous for knee valgus motion and pKAM; Greater values are advantageous for knee flexion range of motion and leg stiffness

Table 6: Knee flexion range of motion, knee valgus motion, pKAM and leg stiffness mean percentage change between treatment (Low risk versus High risk). Confidence limits (CL), chances that the true effects were substantial, and practical assessments of the effects are also shown.

Paired comparison	Mean Change (%)	±90% CL	Effect Size (d)	Chances that the true effects were substantial ^a (%)...			
				Positive	Trivial	Negative	Qualitative inference ^b
Knee flexion range of motion	12.2	1.1 to 24.5	0.44	84	16	0	Likely worthwhile differences
Knee valgus motion	-33.3	-52.7 to -6.1	-1.1	1	7	92	Likely worthwhile differences
pKAM	-30.3	-42.1 to -16.0	-0.59	0	2	98	Very Likely worthwhile difference
Leg stiffness	10.8	-2.0 to 25.3	0.61	82	14	3	Likely worthwhile difference

± 90% CL: add and subtract this number to the mean effect to obtain the 90% confidence limits for the true difference.

^a Substantial is an absolute change in performance of 0.2 standardised Cohen's units (see Methods).

^b If chance of benefit and harm both >5%, true effect was assessed as unclear (could be beneficial or harmful). Otherwise, chances of benefit or harm were assessed as follows: <1%, almost certainly not; 1-5%, very unlikely; > 5-25%, unlikely; >25-75%, possible; >75-95%, likely; >95-99%, very likely; >99%, almost certain.

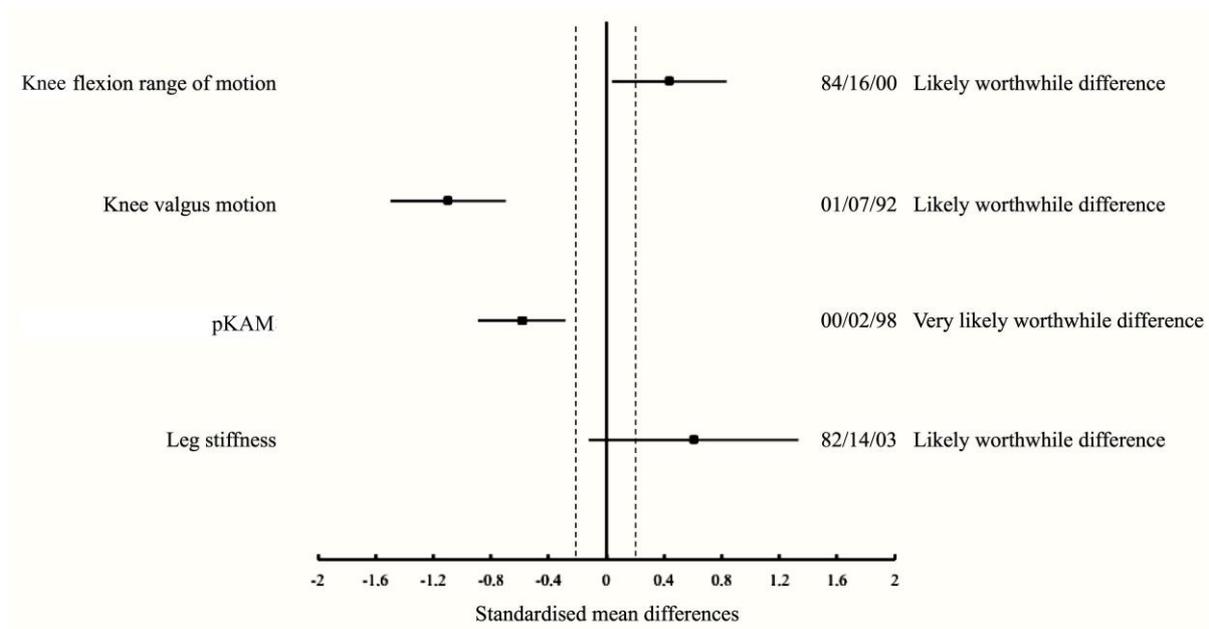


Figure 3: Differences between high and low risk groups based on standardised mean differences (positive/trivial/negative)

Discussion

The findings from the current study indicate that knee valgus, leg stiffness and pKAM can all be improved with a multi-component robustness program. To our knowledge this is the first study to identify significant beneficial effects of such training in young elite female soccer players (11-16y-old) using magnitude based inference analysis to infer clinical significance. Additionally, the current findings indicate that the beneficial effects of robustness training in female youth soccer players is greater in those identified as high risk, opposed to those classified as low risk, based on high pKAM probability. These findings have important implications for the interpretation of findings from previous intervention programs which might have under-estimated the efficacy of such programs by focusing on group changes that

include both high and low risk individuals in the analysis. A more nuanced analysis of these data may have identified that those with potentially room for greater improvements (eg those identified as high risk) may have benefited more from the group style intervention than those classified as low risk.

The possible worthwhile differences identified from the MBI approach indicates that a multi-component training program can reduce the risk of high pKAM through training compared with a control group (10.1%). Our findings are in agreement with the pilot study of Myer et al.²⁶ who reported a 13% reduction in KAM following 8 weeks of neuromuscular training in a small sample (n=18) of 16y-old girls. However, our data are in conflict with a previous study, using similar aged female athletes¹⁵. The differences between the findings in the current study and that of Hewett et al.¹⁵ might be explained in part by the specifics of the intervention program used. The Hewett et al.¹⁵ program was a targeted trunk and hip focused intervention and their findings demonstrated significant improvements in trunk and hip kinematics. Our robustness training program was designed to improve both biomechanical movement as well as strength, stabilization and balance and may in part explain why we found significant improvements in pKAM risk. It should also be noted that Hewett et al.¹⁵ directly determined pKAM whereas we used a validated nomogram to predict pKAM risk which might also account for the differing finding.

Importantly our findings support the early pilot study of Myer et al.²⁶ by showing that those individuals identified with a high risk of pKAM can significantly reduce that risk compared to those identified as low risk (30.3%). The improvements in the reduction of pKAM between low and high risk individuals in the current study compared to those of Myer et al.²⁶ (30% vs 13%) might be attributed to the duration and total load of the interventions (16 vs 8 weeks; 48

vs 18 sessions). The current data support the premise set out by Myer et al.^{27,28,29} who suggest that identifying and targeting injury prevention at those identified as at risk for high pKAM is fundamental in preventing and reducing ACL injuries in female youth. The strengthening and plyometric exercises in our intervention are likely contributing factors in the reduction of potentially high pKAM and supports the work of Hewett et al.¹⁶ who suggest that plyometric exercise increases hamstring strength and reduces pKAM on landing. Our data also highlight that by grouping high and low risk athletes together potentially under-estimates the positive benefits of such intervention programmes for those identified as high risk. These data reinforce the need to examine individual responses to such programmes, even when a team approach to prevention is employed. The difference between the intervention group and the control group in terms of high pKAM risk after the program was 10.1% whereas the difference between the high risk group and the control group was 30.3%. It is therefore possible that previous studies exploring the efficacy of such programmes have under-estimated the positive benefits of such programmes for high risk athletes.

The current study demonstrates a large beneficial training effect on knee valgus with a reduction of 55% evident in the training group. This is important given that low knee separation and large knee valgus has been associated with lower limb injury incidence in adolescent female soccer players³⁰. Our findings agree with a number of previously published studies indicating that valgus can be reduced through neuromuscular training^{24,25} although conflicting data are available in adult females². However, the 55% reduction in our study is much larger than those previously reported (ranging from 17 to 28%) and may be attributed to our multi-component programme that includes dynamic stretching, strength, plyometric and stabilization exercises targeting the lower extremity, posterior chain, hip abductors and trunk. The likely worthwhile differences between the high and low risk groups (33.3%) in improvements in

valgus indicate that high risk athletes gain greater beneficial effects of the robustness training. It is probable that improvements in hip abduction strength contributed to improved control of knee valgus alignment³¹ and that improvements in gluteus maximus and medius additionally contributed to keep the hip abducted during landing tasks¹. As our programme included a component focusing on improving core stability it is likely that the improvements in valgus may be due to enhanced stabilization of the trunk allowing young female soccer players to withstand the large ground reaction forces sustained during landing. Interestingly our findings indicate that without robustness training knee valgus can become more compromised as we found a 9% increase in valgus in the control group. This may possibly be attributed to the influence of growth and maturation. It is likely that the disproportionate increase in limb length during growth and the increase in hip width through maturation (subsequently increasing Q angle) might in part explain the increase in valgus identified in the control group. These data further reinforce the need to implement robustness training at a young age to offset the potential detrimental effects of normal growth and maturation in youth female athletes.

It is difficult to explain our findings in relation to knee flexion ROM as there were possibly worthwhile differences between the groups with the control group increasing ROM more than the intervention group (7%). The greater knee flexion ROM in the control group may be due in part to the smaller improvement in limb stiffness observed throughout the study which is likely due to longer ground contact. The increased stiffness seen in the intervention group may therefore explain the reduced effect of knee flexion ROM in this group. Biomechanical landing training was part of the intervention study and it may be that coaches focused more on knee valgus during landing rather than correcting poor knee flexion. However the likely worthwhile differences between high and low risk groups suggests that those identified as high risk do see greater benefits of such training compared with low risk individuals (12.2%) in ROM.

We also observed likely worthwhile differences for leg stiffness between the intervention and control group (11.4%). Based on previous literature we would expect to see an increase in stiffness in the control group with increasing age and maturation^{7,21}. To our knowledge this is the first study to have demonstrated improvements in leg stiffness in youth female soccer players after a robustness training intervention. The likely worthwhile differences between the high and low risk groups further reinforces our finding that high risk individuals exhibit greater improvements from such training than low risk individuals (10.8%). It is likely that the increased plyometric load in the training group was a contributing factor in increasing the stretch shortening cycle capability in our intervention group. As leg stiffness is governed in part by pre-activation and short-latency stretch reflexes²¹ it is likely that the improvements in leg stiffness may contribute to a change in the activation of the musculotendon unit. Such changes are typically characterized by an increase in pre-activation prior to ground contact (feed-forward control) and an increase in co-contraction after ground contact (feedback control), both contributing to greater stability upon landing.

We acknowledge that there are certain limitations to this study as there is a need to collect longitudinal data in pediatric populations and to link the improvements observed by the program to injury incidence. There are also limitations in taking a 2D approach to exploring knee valgus during landing tasks and a 3D approach provides the additional ability to explore tibial internal rotation. Due to the nature of the field based testing in venues across a large region in the UK it was not possible to use a 3D system in the current study. It was also not possible to directly measure training load due to the lack of access to GPS systems, so load was only determined using training diaries in the current study. Using GPS would have provided us with a more robust assessment of load over the duration of the intervention period, especially as the intervention group were given two extra home-based sessions of training per week

compared with the control group. Due to testing restraints (including time and location demands) we were unable to directly determine knee abduction moments and therefore relied upon the nomogram developed by Myer et al. to determine the probability of high knee abduction moments. Previous laboratory based studies have determined high risk as an abduction load greater than 25.25Nm^{26} . As the probability of high KAM was used in the current study to determine high and low risk, rather than direct determination of KAM using force plate data (which was not feasible due to the field based testing), values greater than 80% were deemed as high risk. We fully acknowledge that further age and sex group specific studies are required to classify individuals into high and low risk using cut-off values determined from pKAM and injury incidence data. Finally, the limited sample size of each group and the number of teams and centers involved in this study did allow us to carry out a multilevel analysis to control for clustering effects. However, the presence of experienced youth physical performance and soccer coaches in each session to deliver and monitor the robustness training, together with the fact that every team and center followed the same training/match regimen may have minimized the clustering effects.

The findings of the current study would suggest that a multi component robustness training programme can improve risk factors associated with injury incidence in young female soccer players. Importantly those benefits are greater in those individuals classified as high risk for pKAM and therefore some form of individual athlete risk identification is recommended. It may be that such young players might benefit from additional bespoke training alongside team interventions to further reduce risk of injury, however this requires further investigation including individualised training for high risk individuals. One of the limitations of the current study is that we were unable to run the risk analysis based on maturational stage due to the relatively small sample size in the risk analysis. Future work should explore if there are

maturational based implications for the efficacy of such training in high and low risk groups. One of the next steps is also to explore if such benefits reduce injury incidence. However, based on our data, we would recommend the following to practitioners: 1) identification of high risk athletes is important as they may gain greater benefits from individualised training; 2) that young females should be considered a high risk group and that multi-component training should be implemented as it can reduce injury risk; 3) doing no prevention training during growth and maturation may be considered 'harmful' in terms of knee valgus risk.

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