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Effect of supervision and athlete age and sex on exercise-based injury prevention programme effectiveness in sport: A meta-analysis of 44 studies

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ABSTRACT

We aimed to evaluate the influence of supervision, athlete age and sex and programme duration and adherence on exercise-based injury prevention programme effectiveness in sport. Databases were searched for randomized controlled trials evaluating exercise-based injury prevention programme effectiveness compared to "train-as-normal". A random effects meta-analysis for overall effect and pooled effects by sex and supervision and meta-regression for age, intervention duration and adherence were performed. Programmes were effective overall (risk ratio (RR) 0.71) and equally beneficial for female-only (0.73) and male-only (0.65) cohorts. Supervised programmes were effective (0.67), unlike unsupervised programmes (1.04). No significant association was identified between programme effectiveness and age or intervention duration. The inverse association between injury rate and adherence was significant (β=-0.014, $p = 0.004$). Supervised programmes reduce injury by 33%, but there is no evidence for the effectiveness of non-supervised programmes. Females and males benefit equally, and age (to early middle age) does not affect programme effectiveness.

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Sport injury prevention; supervision; sex; age

Introduction

In elite sports, injuries impair performance, reduce player availability and significantly increase costs (Hickey et al., 2014; Maffulli et al., 2010). Similarly, injuries in recreational sport pose a public health problem and economic burden [estimated to exceed $20 million in medical costs annually in one American state (Ryan et al., 2019)] and may limit future engagement with exercise (Caine et al., 2014). Previous meta-analyses have found exercise-based injury prevention programmes (IPP) to be effective in reducing injury in sport (e.g. Crossley et al., 2020; Lauersen et al., 2014, 2018; Vatovec et al., 2020); however, the degree of effectiveness varied, suggesting the

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influence of contextual factors. The influence of some factors is known, e.g. IPP content; strength, proprioception and multi-component programmes have robust supporting evidence for reducing injury (Crossley et al., 2020; Lauersen et al., 2014, 2018), whereas stretching does not (Brunner et al., 2019; Lauersen et al., 2014). However, the influence of other factors such as athlete age and sex, or whether the IPP is supervised or not, are less well understood.

Coaches or sport scientists tend to lead IPPs in sports teams, thus IPPs are implemented in a structured manner that facilitates athlete engagement. An example of a well-established IPP is the FIFA11+, a dynamic warm-up originally designed to prevent injury in soccer (Silvers-Granelli et al., 2017) that has also been successfully applied to other team sports, e.g. basketball, lacrosse, American football and futsal (Longo et al., 2012; Lopes et al., 2020; Slauterbeck et al., 2019). With the application of IPPs to an increasing number of sports (evidenced by the increasing number of randomized controlled trials in the area), it is important to evaluate the effectiveness of IPPs across this more diverse sporting landscape. This is especially relevant where implementation is more challenging, e.g. unsupervised recreational runners (Linton et al., 2022). Lack of supervision may lead to exercises not being performed correctly or at the appropriate level of difficulty, which may cause inadequate tissue exposure to appropriate injury prevention exercises similar to reduced adherence to IPPs where a dose-dependent response has been identified (Lauersen et al., 2014; Steffen et al., 2013).

There has been surprisingly little attention paid to the possible effects of participant sex on the effectiveness of IPPs. A meta-analysis of meta-analyses showed that IPPs were effective in reducing ACL injury in females, but there was insufficient evidence for males (Webster & Hewett, 2018), suggesting sex is a potential confounder in ACL IPP effectiveness. It remains unclear, however, whether males and females benefit similarly from IPPs across a range of injuries and sports. Should a divergence be apparent in favour of males or females, then alternative and/or additional components to IPPs may be required. Similarly, the potential influence of age on IPP effectiveness has received little attention. Greater benefits of a neuromuscular programme on ACL injury in younger (mid-teens) versus late teens or early adult female athletes were reported (Myer et al., 2013); however, no previous analysis has been able to provide conclusions across a wider age range on any interaction between age and IPP effectiveness more generally. The potential effects of age on IPP effectiveness may become increasingly important with the encouragement to engage in sport/exercise throughout the lifespan.

Previous meta-analyses evaluating the effectiveness of IPPs have either focused on one sport and/or injury/IPP type (e.g. Crossley et al., 2020; Vatovec et al., 2020) or included a range of sports and injuries but were published almost a decade ago (Lauersen et al., 2014). With a substantial increase in the number of randomized controlled studies evaluating IPP effectiveness across an increasing number of sports in recent years, a refreshed evaluation is needed with additional subgroup and regression analyses to comprehensively explore athlete characteristics and other potential confounding factors. Therefore, the primary aims of this systematic review were to determine the overall effectiveness of IPPs and to evaluate the influence of supervision, sex and age on IPP effectiveness without restricting to any sport, injury or IPP type. The secondary aim was to evaluate the influence of adherence and intervention duration on IPP effectiveness. The findings may indicate the extent to which exercise-based IPPs could be more widely used in practice (e.g. across different sports and for a more diverse range of athlete characteristics).

Materials and methods

Study selection

This review was conducted according to the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) guidelines (Moher et al., 2009). Search terms (see supplementary material) and inclusion/exclusion criteria were determined *a priori* and used to search PubMed, Web of Science (including Medline) and Sports Discuss from inception to 19 October 2022. Inclusion criteria were randomized controlled trials, written in English, reporting of musculoskeletal sports injuries, participants engaging in a named sport, exercise interventions compared to an "as normal" control group and participants of any age and sex. Exclusion criteria included non-randomized trials, review articles, protocols, editorials and conference abstracts, workplace interventions (e.g. physical education teachers), participants engaging in general physical activity (e.g. physical education), army recruits, inclusion of only injured participants from the outset, passive interventions (e.g. tape) and animal studies.

The initial search was conducted by one assessor (SV) who transferred the list of studies to Zotero (v 6.0.15) and merged duplicate entries. Titles and abstracts were reviewed independently by a primary and secondary assessor (SV, LL), after which the list of eligible studies for full review was agreed. The same two assessors independently reviewed the full texts of the remaining studies and agreed to the final list of included studies. An arbitrator (NS) was available where needed. Hand searching of the reference lists of included studies and of previously published systematic reviews and meta-analyses from the initial search were conducted to identify any further eligible studies. Corresponding authors were contacted if primary outcome data were not available. When authors did not respond or the data were no longer accessible, those studies were excluded.

Data extraction

Data extraction from eligible studies was performed by the primary assessor (SV) and entries checked by the second assessor (LL). An arbitrator (NS) was available where needed. The primary outcomes were total number of injuries and total exposure hours (training and match or specific sports engagement as given in each study) for the intervention and control groups. Where data for injury number or exposure hours were not available but injury rate was given, injury number or exposure hours were calculated and rounded to the nearest whole number.

The secondary outcomes were number of participants, age, sex, type of sport, type of intervention, duration of intervention (weeks), whether the intervention was supervised or not (supervised was defined as in-person and led by a coach, researcher or similar, and unsupervised was defined as no in-person supervision and the athlete was given an exercise programme to perform independently), intervention adherence (the percentage of sessions the IPP was participated with from the total number of expected sessions to be engaged with) and injury type. A weighted mean age was calculated per study across intervention and control groups where group mean age data were available.

Risk of Bias

Studies were assessed for Risk of Bias (RoB) using Version 2 of the Cochrane risk-of-bias tool for randomized trials (RoB 2) (Higgins et al., 2022). This tool scores RoB for studies as "high", "some concern" or "low" for each of five categories: randomization process, deviations from intended intervention, missing outcome data, measurement of the outcome and Selection of the reported result, after which it assigns an overall categorization of RoB based on the highest RoB classification from the sub-categories. Screening for RoB was performed independently by two assessors (SV and LL) and outcomes were discussed and agreed.

Statisticalanalysis

Review Manager version 5.4.1. (The Cochrane Collaboration, 2020) was used to perform the meta-analysis. Rate ratio (RR) was determined and a random-effects model on pooled data used to identify between-group (intervention *versus* control) differences with all studies included. Rate ratios less than 1 indicated a reduction in injury risk in favour of the IPP. The random effects model was repeated on pooled data of studies grouped by sex (male only, female only and studies including male and female participants) and by supervision (yes, no). Cochran's Q and I^2 were obtained to identify heterogeneity. Funnel plot asymmetry was assessed in R using the arcsine test (Rücker et al., 2008) and by visual inspection of the funnel plot. A random effects meta-regression was performed using Jamovi version 2.3.18 (The Jamovi Project, 2022) for mean age, intervention duration and intervention adherence on IPP effectiveness. Throughout, alpha was set to 0.05. Forest plots were generated using Review Manager 5, and RoB plots were created using the Cochrane risk-of-bias tool for randomized trials (RoB 2).

Results

The study selection process is shown in Figure 1. From the initial 8303 studies, 44 studies were included in the final set, totalling 40,409 participants (intervention $n = 20,671$; control $n = 19738$). Almost half of the studies evaluated soccer alone ($n = 21$). Most studies ($n = 32$) included a multi-component programme. Further study details are given in Table 1.

Overall exercise intervention effect

Pooled analysis from 44 studies showed a significant beneficial effect of IPP on injury reduction (risk ratio 0.71 [95% confidence interval 0.64, 0.78], $p < 0.001$); see Figure 2. The study heterogeneity was significant ($Q = 214.41$, $df = 43$, $p < 0.001$, $I^2 = 80\%$).

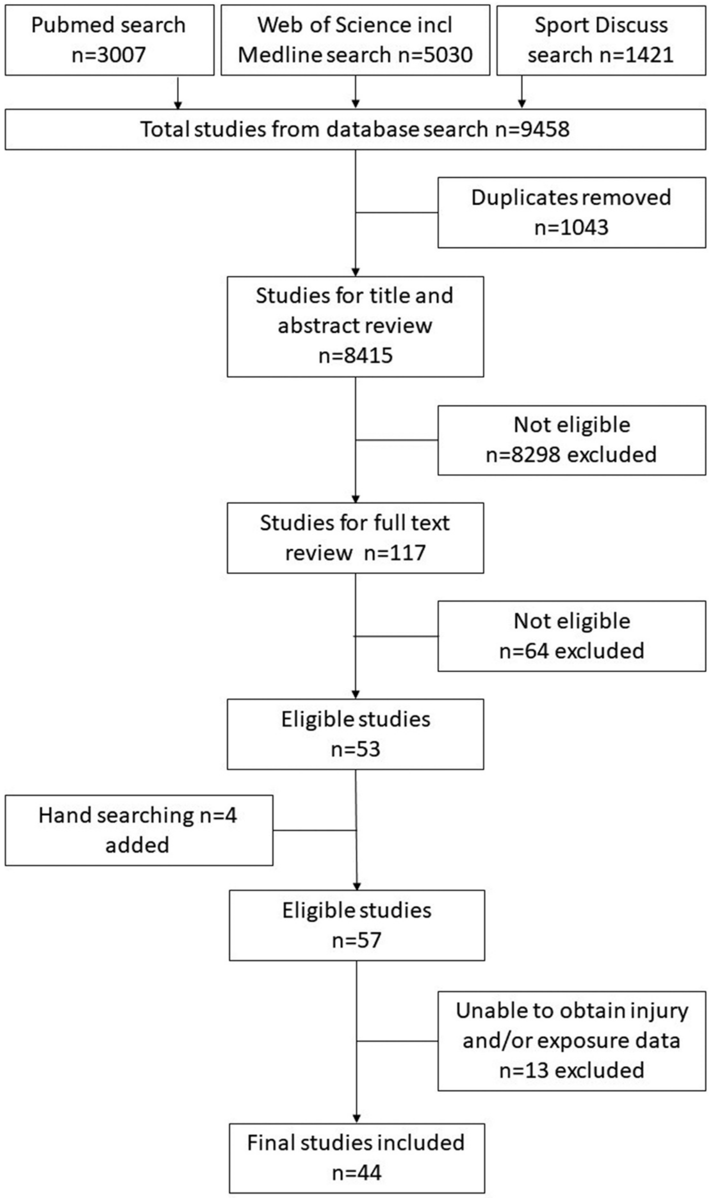

Figure 1. Flow diagram of study selection process.

Stratified by sex

Eight studies included female participants only, 18 studies included male participants only and 18 studies included both sexes. Pooled study effects of female-only were 0.73 [0.56, 0.95], $p = 0.020$ (heterogeneity: Q = 42.46, df = 7, $p < 0.001$, $I^2 = 84\%$), male only were 0.65 [0.54, 0.78], $p < 0.001$ (heterogeneity: Q = 108.16, df = 17, $p < 0.001$, $I^2 = 84\%$) and both sexes were 0.74 [0.65, 0.85], $p < 0.001$ (heterogeneity: Q = 62.87, df = 17, $p < 0.001$, $I^2 = 73\%$). There was no

Table 1. Summary of studies.

Study	Participants (n)	Sex	Age (years; mean or median)	Sport	Intervention: Description	Intervention: Duration	Intervention: Sup	Intervention: Mean adherence (%)	Injury outcome	Injuries: Int	Injuries: Con	Exposure (hrs): Int	Exposure (hrs): Con
Fujisaki et al. (2022)	Int 72 Con 57	M	Mean 16.0	Soccer	Strength	16 weeks	Yes	98	Groin injury	4	18	16000	14516
Al Attar et al. (2021)	Int 379 Con 386	M	Mean 26.5	Soccer (Goal-keepers)	****FIFA 11+S	6 months	Yes	80	Any upper limb injury	50	122	80555	62887
Hilska et al. (2021)	Int 681 Con 737	M & F	Mean 12.3	Soccer	Cardiovascular, plyometrics, landing, strength, core	20 weeks	Yes	63	Lower limb injury	310	346	70454	62909
Nuhu et al. (2021)	Int 312 Con 318	M	Mean 19.8	Soccer	*FIFA 11+	7 months	Yes	77	Any injury	168	252	65333	63389
Åkerlund et al. (2020)	Int 301 Con 170	M & F	Mean 13.5	Floorball	Proprioception, landing, strength, core	26 weeks	Yes	84	Any injury	197	152	16280	8128
Gouttebarge et al. (2020)	Int 266 Con 283	M & F	Mean 28.5	Volleyball	Cardiovascular, core, strength, proprioception	8 months	Yes	73	Any injury	316	430	28654	25479
Hasebe et al. (2020)	Int 156 Con 103	M	Mean 16.5	Soccer	Nordic Hamstring Exercise	27 weeks	Yes	88	Hamstring injury	4	3	45374	28910
Lopes et al. (2020)	Int 31 Con 30	M	Mean 26.5	Futsal	*FIFA 11+	20 weeks	Yes	89	Any injury	24	34	3768	3081
Pas et al. (2020)	Int 286 Con 293	M & F	Mean 41.5	Tennis	Cardiovascular, strength, proprioception	12 weeks	No	Not available	Any injury	263	286	10366	11710
Taddei et al. (2020)	Int 57 Con 61	M & F	Mean 40.9	Running	Strength and	8 weeks	Yes & No	89	Any injury	8	20	5304	6747
Zarei et al. (2020)	Int 443 Con 519	M	Mean 12.2	Soccer	**FIFA 11+ Kids	9 months	Yes	Not available	Any injury	30	60	31934	32113
Halvarsson and von Rosen (2019)	Int 30 Con 32	M & F	Mean 24.2	Orienteering	Proprioception, plyometric, strength	14 weeks	No	55	Lower limb injury	28	36	2969	3219
Sakata et al. (2019)	Int 109 Con 110	M & F	Mean 10.3	Baseball	Static stretches, dynamic stretching, proprioception	12 months	Yes	Not available	Shoulder and elbow injury	27	46	15882	14839
Slauterbeck et al. (2019)	Int 1825 Con 1786	M & F	Not stated	American football (M), soccer, basketball, lacrosse (M & F)	*FIFA 11+	12 weeks	Yes	45	Lower limb injury	196	172	116079	113420
van de Hoef et al. (2019)	Int 229 Con 171	M	Mean 23.1	Soccer	Plyometric	39 weeks	Yes	Not available	Hamstring injury	31	26	27679	18705
Achenbach et al. (2018)	Int 168 Con 111	M & F	Mean 15.0	Handball	Proprioception, plyometric, landing, strength, core	Not stated	Yes	Not available	Any injury	50	32	26278	17929

(*Continued*)

Table 1. (Continued).

					Intervention					Injuries		Exposure (hrs)	
Study	Participants (n)	Sex	Age (years; mean or median)	Sport	Description	Duration	Sup	Mean adherence (%)	Injury outcome	Int	Con	Int	Con
Attwood et al. (2018)	Int 682 Con 673	M	Mean 25.5	Rugby	Proprioception, strength, landing/cutting technique, plyometric	42 weeks	Yes	Not available	Any injury	122	133	9900	9660
Bonato et al. (2018)	Int 86 Con 74	F	Mean 20	Basketball	Cardiovascular, dynamic stretching, strength, plyometric, landing technique, agility	Not stated	Yes	78	Any injury	32	79	19277	16844
Rössler et al. (2018)	Int 2066 Con 1829	M & F	Mean 10.8	Soccer	Proprioception, balance, plyometric, strengthening, core, falling technique	Not stated	Yes	Not available	Any injury	139	235	140716	152033
Hislop et al. (2017)	Int 1325 Con 1127	M	Mean 16.0	Rugby	Proprioception, strength, plyometric, landing/ cutting technique	14 weeks	Yes	69	Any injury	291	262	37346	32375
Finch et al. (2016)	Int 679 Con 885	M	Not stated	Australian football	Proprioception, plyometric, landing exercises	26 weeks	Yes	Not available	Any injury	335	438	12790	15537
Zouita et al. (2016)	Int 26 Con 26	M	Not stated	Soccer	Strength	12 weeks	Yes	Not available	Any injury	4	13	5700	5590
Hammes et al. (2015)	Int 146 Con 119	M	Mean 44.3	Soccer	*FIFA 11+	9 months	Yes	98	Any injury	51	37	4172	2937
H. Silvers-Granelli et al. (2015)	Int 675 Con 850	M	Mean 20.6	Soccer	*FIFA 11+	5 months	Yes	Not available	Any injury	284	665	35226	44212
van der Horst et al. (2015)	Int 292 Con 287	M	Mean 24.6	Soccer	Nordic Hamstring Exercise	13 weeks	Yes	91	Hamstring injury	11	25	44000	31250
Owoeye et al. (2014)	Int 212 Con 204	M	Mean 17.7	Soccer	*FIFA 11+ warm-up	6 months	Yes	60	Any injury	36	94	51017	61045
Aerts et al. (2013)	Int 90 Con 93	M & F	Mean 24.7	Basketball	Plyometric, landing technique	3 months	Yes	86	Any injury	18	28	5010	5227
van Beijsterveldt et al. (2012)	Int 223 Con 233	M	Mean 24.8	Soccer	***FIFA 11	9 months	Yes	73	Any injury	207	220	21563	22680
Bredeweg et al. (2012)	Int 171 Con 191	M & F	Mean 38.1	Running	Plyometric	4 weeks	No	Not available	Any injury	26	32	839	1067
Longo et al. (2012)	Int 80 Con 41	M	Mean 14.1	Basketball	*FIFA 11+	9 months	Yes	100	Any injury	14	17	23640	12648
Walden et al. (2012)	Int 2479 Con 2085	F	Mean 14.1	Soccer	Strength, core, plyometric, proprioception, landing technique	7 months	Yes	Not available	Knee injury	49	47	149214	129084
LaBella et al. (2011)	Int 737 Con 755	F	Mean 16.2	Soccer, basketball	Strength, plyometric, proprioception, agility exercises, landing technique	Not stated	Yes	Not available	Lower limb injury	50	96	28023	22925
Eils et al. (2010)	Int 81 Con 91	M & F	Mean 24.1	Basketball	Proprioception	Not stated	Yes	Not available	Ankle injury	7	21	4565	4876

(*Continued*)

Table 1. (Continued).

Study	Participants (n)	Sex	Age (years; mean or median)	Sport	Intervention: Description	Duration	Sup	Mean adherence (%)	Injury outcome	Injuries: Int	Injuries: Con	Exposure (hrs): Int	Exposure (hrs): Con
Emery and Meeuwisse (2010)	Int 380 Con 364	M & F	Not stated	Soccer	Dynamic stretching, strength, agility, core jumping, proprioception, landing technique	20 weeks	Yes & No	Not available	Any injury	50	79	24051	23597
Gilchrist et al. (2008)	Int 583 Con 852	F	Mean 19.9	Soccer	Running, Static stretching, strengthening, plyometric, agility	12 weeks	Yes	72	Knee injury	40	58	26538	41948
Pasanen et al. (2008)	Int 256 Con 201	F	Mean 23.8	Soccer	Running technique, proprioception, plyometrics, static stretching, strengthening, landing technique	6 months	Yes	73	Lower limb injury	87	102	32327	25019
Soligard et al. (2008)	Int 1055 Con 837	F	Mean 15.4	Soccer	Strength, plyometric, proprioception, dynamic stretching, agility, landing technique	8 months	Yes	77	Any injury	161	215	49899	45428
Steffen et al. (2008)	Int 1073 Con 947	F	Mean 15.4	Soccer	*FIFA 11+ and balance mat	8 months	Yes	52	Any injury	242	241	66423	65725
Emery et al. (2007)	Int 494 Con 426	M & F	Median 16.0	Basketball	Proprioception	18 weeks	Yes & No	Not fully available	Any injury	130	141	39369	34955
McGuine and Keene (2006)	Int 373 Con 392	M & F	Mean 16.5	Soccer and basketball	Proprioception	Not stated	Yes	Not available	Ankle injury	23	39	20250	20828
Olsen et al. (2005)	Int 958 Con 879	M & F	Mean 16.3	Handball	Strength, proprioception, plyometric, landing technique	8 months	Yes	Not available	Any injury	103	195	93812	87483
Verhagen et al. (2004)	Int 392 Con 340	M & F	Mean 24.3	Volleyball	Proprioception	9 months	Yes	Not available	Any injury	132	102	62477	42960
Soderman et al. (2000)	Int 62 Con 78	F	Mean 20.5	Soccer	Proprioception	7 months	No	63	Any injury	28	31	5895	8094
van Mechelen et al. (1993)	Int 159 Con 167	M	Not stated	Running	Stretching[¶]	16 weeks	No	Not available	Any injury	26	23	4727	4694

Note: *M* = Male, F = Female, Sup = Supervised, Int = Intervention, Con = Control. Proprio = Proprioception, Multi = Multi-component, Plyo=plyometrics.
*.FIFA 11+: Dynamic stretching, proprioception, strength, plyometric, planting/cutting/agility exercises.
†.FIFA 11+ Kids: Proprioception and coordination, strength, landing and falling techniques.
‡.FIFA: Core, proprioception, strength, plyometric, landing technique.
§.FIFA 11+S: Upper limb neuromuscular control, core stability, eccentric rotator strength and agility.
¶.Adherence is defined as the percentage of sessions from the total number of possible sessions where the intervention was delivered. Where these data were not available or could be calculated, these were reported as "Not Available".

significant subgroup difference ($p = 0.490$). A forest plot by sex subgroupings is shown in Figure 3a.

Stratified by supervision

Three studies (Emery & Meeuwisse, 2010; Emery et al., 2007; Taddei et al., 2020) were removed for this analysis as it contained both a supervised and unsupervised component, leaving 41 studies. In 36 studies, the IPP was supervised, and in the remaining five studies, the IPP was unsupervised. Supervised IPPs were effective at reducing injury (0.67 [0.60, 0.75], $p < 0.001$) (heterogeneity: Q = 187.71, df = 35, $p < 0.001$, $I^2 = 81\%$), whereas unsupervised IPPS were not (1.04 [0.90, 1.19], $p = 0.580$) (heterogeneity: Q = 1.23, df = 4, $p = 0.87$, $I^2 = 0\%$). A significant between sub-group difference was present ($p < 0.001$). Of the five unsupervised studies, two were in running (Bredeweg et al., 2012; van Mechelen et al., 1993), one in orienteering (Halvarsson & von Rosen, 2019), one in tennis (Pas et al., 2020) and one in soccer (Soderman et al., 2000). A forest plot by supervision subgrouping is shown in Figure 3b.

Regression by age, intervention duration and adherence

The mean age for the intervention and control groups was available for 38 out of the 44 included studies (intervention group mean age range 10.2–43.1 years; control group mean age range 10.3–45.2 years). There was no significant association between age and IPP effect: β = 0.009[−0.004, 0.022], $p = 0.187$ (heterogeneity: Q = 172.4, $df = 37$, $p < 0.001$, $I^2 = 80\%$).

Intervention duration data were available from 38 studies. Mean intervention duration was 25.3 (±11.5) weeks (range 4–52 weeks). There was no significant association between intervention duration and IPP effect: β = 0.001[−0.008, 0.011], $p = 0.766$ (heterogeneity: Q = 179.3, $df = 37$, $p < 0.001$, $I^2 = 81\%$).

Adherence data were available for 24 studies. Mean adherence was 76.4% (±14.9) (range 45–100%). There was a significant association between adherence and IPP effect: β=-0.014 [−0.023, −0.004], $p = 0.004$ (heterogeneity: Q = 82.7, $df = 23$, $p < 0.001$, $I^2 = 79\%$). Adherence explained 33% of variance in the true effects.

Publication Bias and RoB

No significant publication bias was identified from the statistical analysis (regression intercept = 0.005, $p = 0.172$), however funnel plot visual inspection suggested that some publication bias may be present. Overall RoB was classified as “high”, “some concern” and “low” in 29.5% ($n = 13$), 65.9% ($n = 29$) and 4.5% ($n = 2$) of the 44 studies, respectively (see supplementary files for RoB figure).

Discussion

This meta-analysis of randomized controlled studies on the effect of exercise-based IPPs revealed that (1) IPPs are effective overall in reducing the occurrence of injuries in sport, (2) supervised IPPs are more effective than unsupervised IPPs and more specifically, unsupervised IPPs appear to offer no direct benefit *per se* in injury risk reduction, (3) there is an inverse association between IPP adherence and injury rate, (4) neither duration of IPP or age are related to IPP effectiveness and (5) IPPs are equally of benefit to male, female and mixed cohorts.

Overall IPP effectiveness

Pooled data from the studies included in this meta-analysis demonstrated that IPPs reduce injury risk in sport by 29%. Others, through meta-analyses, have evidenced a similarly protective benefit; Crossley et al. (2020) reported a reduced injury risk of 27% in female soccer players from across primarily multicomponent programmes. Lauersen et al. (2014) identified a 35% and 47% reduction in acute and overuse injuries, respectively, from across a range of IPP types, which is higher than the findings presented here, however, that meta-analysis also included studies with non-sport populations, e.g. military personnel, which may explain some differences. The current analysis extends the findings of previous meta-analyses through the inclusion of a much greater number of studies and a more diverse range of sports. Although this has increased the heterogeneity of pooled data, the search and inclusion criteria match very closely to a previous meta-analysis (with the exception of restrictions to sport populations only) including 23 studies by Lauersen et al. (2014), and the larger number of studies simply reflects the growing body of research in the field.

Supervision, adherence and intervention duration

There was no evidence from this meta-analysis for the effectiveness of non-supervised IPPs in reducing injury risk, although these findings are based on a relatively small number of studies with a diverse set of interventions; two studies included a multi-component IPP (Halvarsson & von Rosen, 2019; Pas et al., 2020), one included a plyometric only IPP (Bredeweg et al., 2012), one included a proprioception only IPP (Soderman et al., 2000) and one included a stretching only IPP (van Mechelen et al., 1993). No studies in the supervised group included a stretching-only IPP. Despite the current evidence on the ineffectiveness of stretching only IPPs (Brunner et al., 2019; Lauersen et al., 2014), the study by van Mechelen et al. (1993) was retained as stretching was considered an active intervention and the study met the inclusion criteria that were set *a-priori*.

The lack of effectiveness of unsupervised IPPs is in contrast to Vatovec et al. (2020), where non-supervised and supervised IPPs for hamstring injuries were found to be equally effective, although only three studies were included in the non-supervised category and data on one injury type were represented. Moreover, that analysis included data from two studies which were not possible to include in this meta-analysis; one could not be included as data were no longer accessible (Askling et al., 2013), and another was included for the main analysis and sex subgroup analysis but not the supervision subgroup analysis as it included both a supervised and unsupervised component (Emery et al., 2007).

The five unsupervised studies in this meta-analysis included a range of sports: two on running (Bredeweg et al., 2012; van Mechelen et al., 1993), one on orienteering

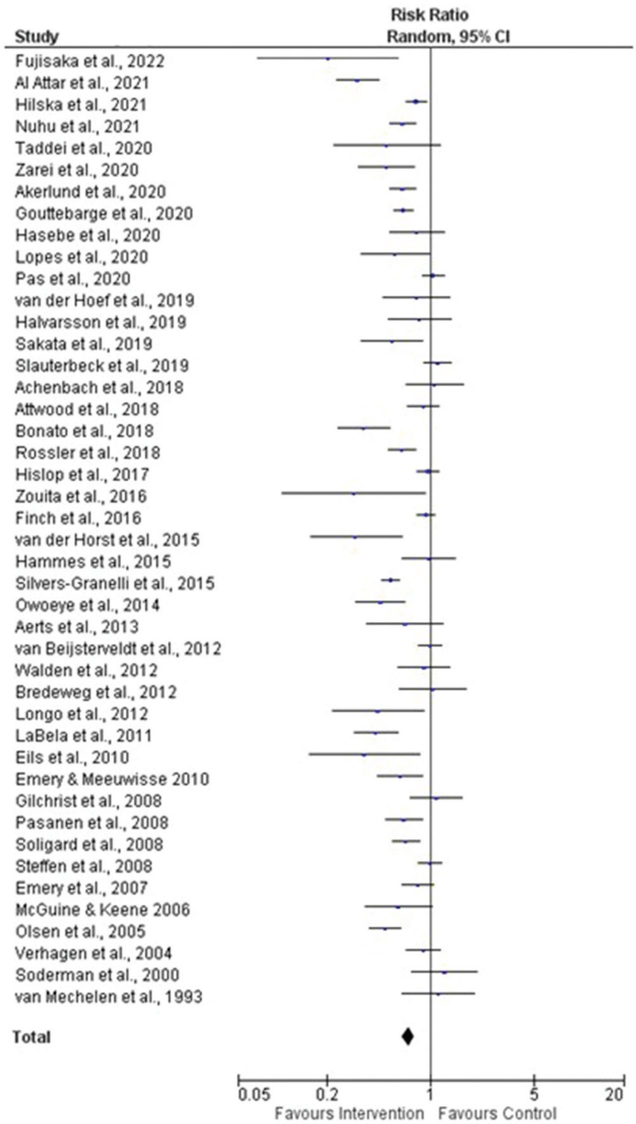

Figure 2. Forest plot of all included studies.

(Halvarsson & von Rosen, 2019), one on tennis (Pas et al., 2020) and one on soccer (Soderman et al., 2000). The difference in sport types included in the supervised and unsupervised groups should be acknowledged due to the relatively greater proportion of running and smaller proportion of soccer in the unsupervised group. It is perhaps not surprising that running featured more commonly in the unsupervised group due to running generally being an individual sport and often not coach-led at recreational level. Previously, the effects of an internet-based source (thus unsupervised) which included advice on training volume, biomechanics and equipment also showed no beneficial effect in reducing injury in runners (Cloosterman et al., 2022; Fokkema et al.,

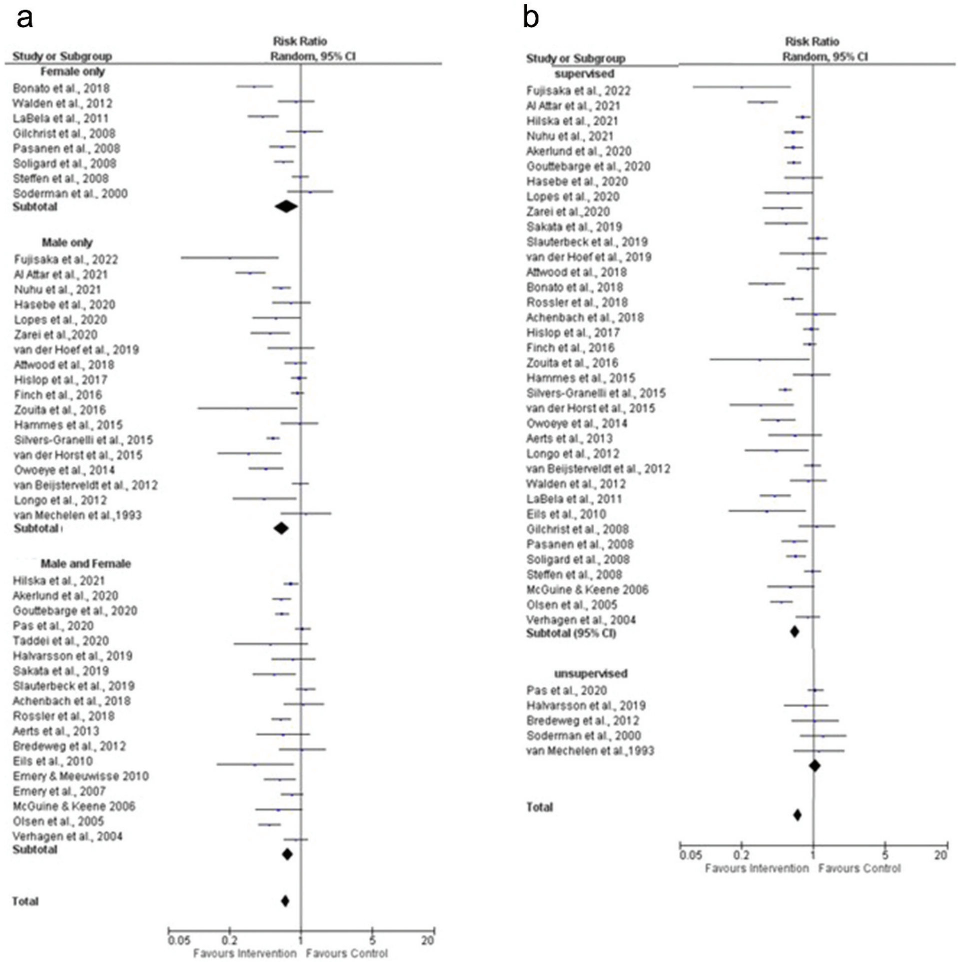

Figure 3. Forest plot of summary analysis by (a) sex and by (b) supervision.

2019). In contrast, Taddei et al. (2020) showed a significantly lower rate of injury in runners following a foot core strengthening IPP, which included a supervised and unsupervised component. It is not clear whether the positive findings in the Taddei et al. (2020) study were due to the uniqueness of IPP or whether it was due to it containing a supervised component. That study was excluded from the supervision subgroup analysis due to it including both a supervised and unsupervised component. Nonetheless, in-person supervision of IPPs is difficult to implement for sports which are generally engaged with independently (i.e. without a coach or similar), therefore further work should determine what type of IPP is best for runners, orienteers and other “solo” sports, and how potential limiting effects of non-supervision can be overcome.

Poor compliance/adherence is one plausible explanation for the lack of significant effect of unsupervised programmes since true engagement with interventions (or correct execution of those exercises) is usually based on athlete reporting and thus may not be a true reflection of the actual executed IPP. This is particularly relevant as we showed a significant inverse relationship between adherence and injury, but no relationship between intervention duration and injury. This would suggest that interventions included in this meta-analysis were generally of sufficient length and longer interventions were as effective as those which were shorter, however non/reduced-compliance reduced their effectiveness. This is similar to other work where increased compliance with FIFA 11+ in soccer reduced injury rates (Silvers-Granelli et al., 2018; Soligard et al., 2010). Unfortunately, of the five unsupervised studies in this meta-analysis, comparisons between high and low compliance were either not performed (Bredeweg et al., 2012; van Mechelen et al., 1993) or were divergent in outcome; Soderman et al. (2000) and Pas et al. (2020) did not find a difference in injury outcomes between high and low compliance rates of their IPPs, yet Halvarsson and von Rosen (2019) reported injury rates in those with lower compliance to be similar to the control group, suggesting poor compliance reduced IPP effectiveness. Compliance in those studies was self-reported, making it challenging to tease out the differential influence of supervision versus true adherence. Future studies evaluating non-supervised IPPs should consider the use of tracking technology in mobile delivery format to monitor adherence more accurately. A further caveat is that reporting of compliance in studies is highly varied, and the lack of standardization regarding what constitutes "good" versus "poor" compliance hinders a more meaningful comparison (Van Reijen et al., 2016).

Sex

The present review demonstrated that exercise-based IPPs significantly and equally reduce injury risk for males, females and mixed cohorts. Due to female athletes being at higher risk of musculoskeletal injuries in general and of the knee in particular (Swenson et al., 2013), it has been suggested that females are in greater need of IPPs (Sommerfield et al., 2020). Despite this increased risk, the results from this review suggest that females benefit equally from exercise-based IPPs, hence specific and targeted programmes by sex do not appear warranted. Similarly, it is unlikely that sex is a confounder in future experimental studies investigating IPP effectiveness, however high heterogeneity across the studies in this review should be noted.

Age

Most exercise-based IPPs included in this meta-analysis evaluated athletes who were adolescents or young adults, and only few studies assessed the effectiveness of such programmes in adults in their 30s or 40s and none beyond. A previous meta-analysis of 14 studies on the effect of age on ACL injury in female athletes identified greater benefits of a neuromuscular programme in younger (i.e. mid-teens) compared to slightly older (late teens or early adult) female athletes (Myer et al., 2013). When that meta-analysis repeated the analysis by dichotomizing into two age groups (≤18 years or >18 years), similarly a difference was found where IPPs were significantly beneficial for the ≤18 years group but not for the >18 years group. It is not quite clear what the full age range was of the included studies in that analysis, but the oldest mean age for any one study was 24 years. In contrast, the meta-regression presented here demonstrated that increasing age does not reduce the benefit of IPPs, up to early middle age. It must be noted that the majority of studies in this analysis included participants with a mean age of less than 30, and only four studies included participants with a mean age of 35–45. The differences between this meta-analysis and the study by Myer et al. (2013) must be considered, however, i.e. the type of analysis (meta-regression versus age group comparison), the number of studies included for age analysis (37 versus 14), sex (males and females versus females only), injury type (all injuries versus ACL injuries) and the upper age limit (40s versus 20s). Therefore, further work with a particular focus on the inclusion of athletes older than 30 is needed, particularly given public health messages regarding exercise for older adults (UK government, 2019).

Risk of Bias

In almost all cases, RoB in studies was either categorized as "some" or "high concern". Frequent causes of higher RoB were the lack of detailed explanation for missing data or lack of detailed information on the randomization process. Blinding of the study participants and coaches was generally not performed, and this is commonly difficult to incorporate in exercise intervention studies. In addition, blinding of the researchers or those collecting and/or analysing injury data was not always evident or reported.

Other areas that were not always clear or consistently reported were injury status of the study participants prior to recruitment and what was considered "injury free". Therefore, the proportion of participants carrying an injury could have varied which may well have influenced outcomes, as those injured may well be at increased risk of re-injury. Typically, due to a whole-team recruitment into a study, it is understandable that consistent criteria as to what constituted being injury free were difficult to achieve. Similarly, the definition of adherence was disparate across studies, and variance across studies may be a limitation. For example, adherence is determined at coach-delivery level, but studies typically did not further define *player* adherence, i.e. the number of sessions each player attended where the intervention was also delivered.

Limitations

This meta-analysis has some limitations that should be highlighted. The number of unsupervised studies was fairly small ($n = 5$). Nonetheless, this work highlights the need for future studies to assess the influence of supervision on IPP effectiveness and in particular for non-coach led sports where supervision is difficult to implement. Future work that considers alternative/improved ways of delivering and adapting supervision for non-coach led sports is also warranted. Heterogeneity was high across studies, and to allow for this, a random effects model was adopted. Sub-group analysis, e.g. for supervision and sex, was used for parts of the analysis presented; however, heterogeneity within sub-groups continued to be high. Further subgrouping was considered, e.g. by sport; however, this would yield too few studies for many categories to draw meaningful conclusions. In addition, mean age data were not available for all 44 studies, and this reduced the pool of studies for that particular analysis to 38. Although this may still be an acceptable number for meta-regression analysis, the vast majority of studies were skewed towards younger ages, and further studies incorporating adults aged 30+ are required to make more robust recommendations. Despite this, the findings from this analysis that age did not affect programme effectiveness showed promise and should be explored going forward.

Conclusion

Pooled information from all included studies showed that exercise-based IPPs have a protective benefit and lower the occurrence of injuries in sport. Encouragingly, this benefit was present irrespective of athlete sex or age, although studies beyond athletes of early middle age were not available. Studies that included supervised IPPs were found to be effective, whereas unsupervised IPPs were not. Whether this is down to poor true engagement with unsupervised IPPs, incorrect execution of exercises or due to the physical demands of sports which might be difficult to implement a supervised IPP for (such as recreational runners), is unclear and requires further evaluation.

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