

ACL injury prevention: Where have we come from and where are we going?

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Abstract

Anterior cruciate ligament (ACL) injuries are one of the most common and severe knee injuries across sports. As such, ACL injury prevention has been a focus of research and sports medicine practice for the past three-plus decades. Examining the current research and identifying both clinical strategies and research gaps, the aim of this review is to empower clinicians and researchers with knowledge of where the ACL injury prevention literature is currently and where it is going in the future. This paper examines the mechanism of ACL injury prevention, screening, implementation, compliance, adherence, coronavirus, and areas of future research. Clinical significance: The time lag between research and practical implementation in general healthcare settings can be as long as 17 years; however, athletes playing sports today are unable to wait that long. With effective programs already established, implementation and adherence to these programs is essential. Strategies such as coaching education, increasing awareness of free programs, identifying barriers, and overcoming implementation obstacles through creative collaboration are just a few ways that could help improve both ACL injury prevention implementation and adherence.

KEYWORDS

anterior cruciate ligament, knee, sports

1 | INTRODUCTION/STATE OF THE RESEARCH

Anterior cruciate ligament (ACL) injuries are one of the most common knee injuries in sports. ACL injuries have doubled over the last two decades, despite the efforts of researchers and clinicians to mitigate risk.¹ Approximately 200,000 to 250,000 ACL injuries occur annually in the United States,² costing of over \$13,000 USD per surgery.³ Nearly a quarter of those injuries occur in children under the age of 18.^{4,5} Whereas the overall incidence of ACL injury is greater in men, primarily due to greater participation in contact and team sports, the relative risk of ACL injuries in women is 2–8 times greater than men.^{4,6}

ACL injury prevention, namely in female athletes, has been well investigated for over three decades.^{7–13} Most of these neuromuscular training programs include a variety of strengthening, plyometric, and agility-based drills that address deficits commonly associated with female athletes who have sustained an ACL injury.^{14,15} Several programs, such as the 11+ (formerly known as the FIFA11+),^{16,17} its predecessor, the prevent injury and enhancement performance program,¹⁸ and the Knäkontroll or Knee Control program,^{19,20} were designed as a dynamic warm-up to increase implementation fidelity, compliance, and adherence.^{21,22} Other programs, including the Sportsmetrics program,²³ were designed as stand-alone programs to be performed outside the training environment.

For an IPP to be effective, the design must consider biomechanical, physiological, socioeconomic, psychological, and ease of implementation perspectives.^{24–26} Although a number of intrinsic and extrinsic risk factors for ACL injury have been proposed, biomechanical risk factors have been a focus.^{27,28} Most IPPs attempt to alter strength and dynamic loading through neuromuscular and proprioceptive training.^{29–33} The studies that have focused on altering strength and pathokinematics have largely resulted in a reduction of ACL injuries.^{8,9,14,19,34–36} However, ACL Injury Prevention Program (IPP) studies vary widely both in their approach to injury prevention and their study design validity. Very few studies to date have been conducted as randomized, controlled trials.^{37,38}

2 | MECHANISMS OF PREVENTION

There is a great deal of research focused on the mechanism of ACL injuries, with some risk factors, such as sex, age, and sport, having more evidence than others.³⁹ Unfortunately, without a complete understanding of the risk factors and mechanism of ACL injuries, researchers and clinicians alike are also without a complete understanding of what exactly makes ACL IPPs effective. Multiple meta-analyses have found that effective ACL IPPs include both strength and plyometric exercises, with mixed results on whether balance training is necessary for ACL injury prevention.^{40–42} Although balance exercises may not,^{40,43} proximal control exercises (defined as exercises that involve segments proximal to the knee joint) seem to improve the efficacy of ACL IPPs.⁴³ Such results could indicate that strengthening, particularly hip and core musculature, could be key in making ACL IPPs effective. However, the interdependence of program components is not well understood, and more importantly, understanding components' efficacy does not necessarily give deep insight into the actual mechanism behind ACL IPPs' effects.

Stiff landings (large vertical ground reaction force, shallow hip and knee flexion) are associated with increased knee joint forces; however, purely sagittal plane forces likely do not injure the ACL.⁴⁴ More so, frontal and transverse plane biomechanics, such as medial knee displacement⁴⁵ or valgus collapse (hip adduction, hip internal rotation, and knee abduction),^{46,47} may be associated with ACL injuries. Thus, researchers hypothesized that effective ACL IPPs would change frontal and transverse plane biomechanics. Interestingly, a 2018 meta-analysis found that peak knee abduction moment was the only frontal plane variable impacted by ACL IPPs.⁴⁸ More often ACL IPPs seemed to change sagittal plane variables, including increased hip flexion (at peak and initial contact), increased peak knee flexion angles, and decreased peak knee flexion moment.⁴⁸ There are a number of limitations to biomechanical studies that must be considered when interpreting the ACL IPP biomechanical literature, including the use of double- versus single-limb tasks; non-sport-related tasks; anticipated versus unanticipated tasks; testing in a laboratory versus on a court or field; a lower cognitive demand during laboratory-based tasks; a lack of retention testing; the analysis of only one limb versus two; and many more.^{48–50} Regardless, further

exploration is needed to determine if changing biomechanics is the mechanism of ACL IPPs.

Whether learning a new task or becoming more efficient, it is logical that for athletes to change their movement pattern, there must be a change in their brain/neural activity.⁵¹ Thus, motor control, neuroplasticity, and brain-behavior have recently garnered more attention, particularly with respect to ACL IPP's mechanism. Grooms et al.⁵² found that an augmented neuromuscular training program led to decreases in hip adduction during cutting, which was related to decreased activity in knee sensory-visual-spatial and motor planning areas, and that decreases in hip adduction and knee rotation were associated with decreased motor cortex activity.⁵² Decreases in motor cortex activity suggest greater efficiency in processing, potentially improving the transfer of practiced patterns to complex sporting environments. In a subsequent larger study, Diekfuss et al.⁵³ found that the augmented neuromuscular training group had larger decreases in peak knee abduction moment than the control group (performing the Sportsmetrics program). The training group also had increases in functional connectivity between brain regions of interest, whereas the control group had no changes. These studies^{52,53} and others⁵⁴ suggest that changes in brain-behavior may be related to changing biomechanics. In particular, employing motor learning principles may make greater biomechanical changes that are also unconscious, allowing the athlete to remain focused on their sport. *While the downstream effects on ACL IPP effectiveness need to be explored, the areas of brain-behavior change and motor learning within ACL IPPs are exciting.*

Historically, motor learning principles have not been a focus in ACL IPP design. Whereas the augmented neuromuscular training discussed in the last paragraph^{52,53} requires significant technology, employing simple motor learning techniques is possible with minimal/no cost. For example, cues directing an athlete's attention externally are effective at changing movement patterns and may better facilitate movements remaining automatic.^{53,55,56} Interestingly, the 11+ manual displays pictures of "proper" movement patterns and gives directions such as "Make sure to keep your upper body straight; your hips, knees, and feet should be aligned; DO not let your knees buckle inwards,"¹⁷ all cues that direct focus internally. In contrast, the originally published Sportsmetrics program used external cues such as "Straight as an arrow," "Light as a feather," "Shock absorber," and "Recoil like a spring."⁵⁷ These cues are external cues, directing the athlete's attention outside their body, and are analogies, a technique known to facilitate implicit learning.⁵⁸ Implicit learning means an athlete develops an internal picture or understanding of a movement/task, rather than following rules or an order of operations. Implicit learning is also known to be effective in promoting automaticity and allowing athletes to perform better dual-task and handle stress.⁵⁸ As of yet, there are no studies comparing external and internal cuing as they relate to ACL injury prevention; however, *external focus of attention/external cueing and implicit learning are easy strategies that can be implemented with little to no equipment and represent aspects of motor learning that clinicians and researchers should continue to explore.*

Video and real-time visual feedback are other techniques that have been explored in ACL injury prevention.^{56,59–61} To name a few, Harris et al.⁶² found that behavior skills training with video feedback improved young female soccer players' skill and retention of a zig-zag drill. The augmented neuromuscular training program used by Grooms et al.⁵² and Diekfuss et al.⁵³ projected a rectangle that deformed in real time based on the athlete's trunk, hip, and knee movements, but the athletes were not given any instructions or explanation regarding the rectangle. Video-based prevention strategies have limitations, in particular, these strategies are easier to implement on an individual basis and require more equipment. Furthermore, Benjaminse et al.⁶¹ found that male basketball players receiving video feedback had changes in their movement patterns, but female players may need different feedback modalities. *The successes of video and real-time feedback studies seem to support further investigation and attention, as well as corroborate the integration of motor learning principles into ACL IPPs, be that through verbal cues, small-sided games, video, or virtual reality.*

Mechanism of Prevention

Clinicians/practitioners

- Effective ACL IPPs include strengthening, plyometric, proximal control, and sometimes balance components.
- Using external cues, directing the athletes' attention outside their body or to the outcome can facilitate changes in biomechanics and movements remaining unconscious.
- Motor learning principles, such as external focus of attention and implicit learning, may be easily implemented in ACL IPPs and require little training and no equipment.
- Video or real-time feedback, particularly when working with an athlete individually, may be beneficial in changing movement patterns and another technique to integrate motor learning principles into ACL injury prevention.

Researchers

- The interdependence of ACL IPP components is not well understood, nor the mechanism behind effective ACL IPPs.
- Although some ACL IPPs have demonstrated changes in biomechanics, the

relationship between efficacy and biomechanical change is still not well understood.

- Further research into the relationship between brain-behavior changes and biomechanics as well as the downstream effects on ACL IPP efficacy is needed.
- The integration of motor learning principles into existing or new ACL IPPs could improve efficacy as well as implementation.
- As technology rapidly develops, video, real-time feedback, and virtual reality may be exciting areas of ACL IPP research.

2.1 | Screening

Identifying ACL injury risk is a controversial topic. A 2016 article by Bahr⁶³ highlighted the need for proper use of screening test properties, and currently there is a recognition in the research community that no test(s) can accurately predict ACL injury risk.⁶³ A number of factors contribute to the absence of accurate screening tests. Without clearly identified risk factors or the interaction thereof, it is very difficult to know what variables are needed to screen. Furthermore, screening studies require large sample sizes, and tests do not yet have the sensitivity and specificity to recognize injury risk.^{64,65} Thus, although there may be value in big data and newer methodologies, such as computer learning algorithms, there is yet to be a proven ACL injury screening tool.

Cost is a significant barrier to ACL IPP implementation but also to screening. *Research currently indicates that it is more cost-effective to implement ACL IPPs in all athletes than to screen and select athletes at risk.*^{66–68} One study modeled four hypothetical strategies for ACL injury prevention in Australia.⁶⁶ The model found that implementing ACL IPPs in all athletes aged 12–25 involved in high-risk sports (rugby, Australian rules football, netball, soccer, basketball, and skiing) not only prevented nearly \$700/person in future healthcare costs, but also had the lowest number needed to treat, and it also prevented the highest number of future knee injuries and total knee replacements.⁶⁶

In addition to identifying athletes at high risk for injury, screening is also used to identify areas for ACL IPP individualization. Particularly in elite sport where more resources (staff, equipment, and time) are available, programs are tailored to what the medical/performance team deems to be the athlete's "needs." Whether programs are tailored strength training^{9,30} or based on biomechanics,⁶⁹ *further research is needed into the efficacy of individualized ACL IPPs.* Individualized ACL IPPs are much harder to study as each cohort is $N = 1$. However, from a motor learning standpoint, giving each athlete the opportunity to find their own motor solutions to movement problems may be more

effective.^{56,59,60} ACL IPPs looking to foster neuroplasticity must facilitate exploratory learning, which could involve video, small-sided games, or the creation of representative learning environments.^{56,70} *ACL IPPs such as these could capture coaches' attention as they would likely involve more technical skill work; however, motor learning-based ACL IPPs may also be more complex in their set-up and design, requiring collaboration between coaching and clinical/practitioner team, as well as subsequent efficacy research.*

Screening

Clinicians/practitioners

- Clinicians should be wary of tests or algorithms that claim to predict ACL injury.
- It is more cost-effective, both in implementation as well as in future health-care costs, to provide ACL IPPs to all athletes than to screen and select at-risk athletes.

Researchers

- The use of big data and technologically advanced methodologies could enhance researchers/clinicians ability to identify athletes at higher risk for ACL injuries.
- Greater understanding of ACL injury mechanism is needed to understand the complex relationship of risk factors and situational influence.
- Although difficult to study in a large scale, the efficacy of ACL IPP individualization is needed.

2.2 | Implementation

ACL injury prevention is possible, or more precisely, the risk of an ACL injury can be reduced in many sports.^{10,71-73} With good research support to back the use of ACL IPPs, but not screening, the challenge for clinicians and researchers alike is to prove effectiveness in real-world settings. Implementation success takes time. In general health research, the time lag between successful program delivery and use in practice can be as high as 17 years.⁷⁴ There are a few studies, such as the Norwegian female handball ACL injury prevention study, that follow successful implementation of an ACL IPP.⁷⁵ In the study's first season, coaches delivered the

neuromuscular training program. As compliance was low, physical therapists took charge of program delivery during the second intervention season, increasing the compliance and successfully reducing ACL injuries. Following the study, responsibility shifted back to the coaches to continue the IPP. Unfortunately, the number of ACL injuries increased to even higher than preintervention. To mitigate this negative trend, the researchers organized a series of regional coaching seminars, free of charge, to increase knowledge and improve attitudes. The coaches received an instructional DVD and both the prevention and performance benefits were emphasized. Thirteen years after the intervention, the number of ACL injuries among the same group of female athletes was reduced by 50%. The injury reduction was attributed to increased coaching awareness, a new study showing a 50% reduction in severe knee injuries bolstering coaches' "buy-in," increased media attention, and a new prevention webpage.⁷⁵ However, this "success story" is not normal.

Over the last 10 years, the 11+ has been widely distributed by the Fédération Internationale de Football Association or FIFA, which theoretically would increase the global exposure of the IPP in the soccer community.¹⁶ However, in a study among amateur soccer coaches in Germany, more than half of the coaches were unaware of the 11+.⁷⁶ In most sports, the coach is key for IPP implementation and compliance, especially amongst nonelite and youth athletes, where fitness or medical staff are not as robust. Thus, a lack of coaching awareness emphasizes the importance of improving the knowledge translation from national sport federations to local sports clubs. It also emphasizes the value of coaching education. *Coaching education programs should include both theoretical and practical use of ACL IPPs to ensure better knowledge of available programs as well as how to use and implement ACL IPPs.*

The 11+ is an effective IPP, but several studies have pointed out barriers to implementation. O'Brien and Finch^{77,78} analyzed the injury prevention perceptions of soccer coaches, fitness coaches, and physiotherapists from youth male soccer academies⁷⁷ and from professional male soccer teams in four different countries.⁷⁸ All participants fully supported the use of IPPs, acknowledging the need for prevention programs, and agreed that enhancing the impact of IPPs requires a detailed understanding of each team's specific implementation context. Among the youth soccer staff, the impression was that the 11+ needed modification to achieve a better reach, including suggestions like modifying the program's content to contain more challenging exercises, as well as greater exercise variations and progressions.^{77,78} A survey of female soccer coaches in the United States found that cost was the primary barrier to IPP implementation.⁷⁹ Dix et al.⁷⁹ elaborated that "cost" was probably not the cost of the IPP itself, as most prevention programs are available for free. Rather, many coaches who did not use an ACL IPP viewed IPP implementation as the responsibility of others; thus, cost was associated with hiring additional staff, such as strength and conditioning staff.⁷⁹ Coaches who did not use an ACL IPP also identified a lack of practical training in instructing an IPP as a barrier.⁷⁹ *These findings further support including ACL IPPs in coaching education, but also improving awareness that many ACL*

IPPs are free and effective, regardless of whether implemented by a coach or by a medical professional.⁶⁸

A study from Canada examined facilitators and barriers to implementation of the iSPRINT program among junior high school athletes,⁸⁰ a program previously shown to reduce the risk of sport-related injury in youth.⁸¹ Facilitators of implementation success included evidence strength and quality, adaptability, implementation climate, culture, and having a high level of compatibility. Barriers to implementation included intervention complexity, planning, and readiness for implementation. Statements like the IPP was “too time consuming” or “boring” are also well-known barriers.^{82,83} Thus, strategies to help implementation may include modifying the program, decreasing the number of components, or reducing the equipment required.⁸⁰ Researchers could consider developing shorter, yet still effective programs. *Clinicians/practitioners working with teams should collaborate with coaches, athletes, parents, and other stakeholders to identify barriers and strategize implementation solutions.* It is important to keep in mind, though, that changes or modifications in the content of a IPP should be followed by a re-evaluation of the program's effectiveness.⁸⁴

Implementation

Clinicians/practitioners

- Coaching education should include background on ACL IPPs, the benefits of program use, as well as instructions on how to teach the program to their team(s).
- Coach-led ACL IPPs can be as effective in preventing injury as ACL IPPs led jointly by coaches and medical staff.
- Most ACL IPPs are free!
- Key stakeholders, including clinicians/practitioners, coaches, parents, and athletes, should work together to identify barriers and collaborate to strategize implementation solutions.

Researchers

- Common barriers to implementation include duration and number of components; thus, developing and testing shorter or more flexible ACL IPPs could help facilitate use.
- In some environments, such as soccer academies, developing programs with more challenging components and a

greater diversity of exercises and progressions could facilitate ACL IPP implementation.

2.3 | Compliance/adherence

The effectiveness of any intervention is determined jointly by its efficacy and user adherence.⁸⁴ Adherence and compliance are terms often used interchangeably; however, they have important differences (Table 1).⁸⁵ Many studies have proven that severe knee injuries can be prevented^{42,86,87}; however, few studies have investigated the compliance, and none, to the authors' knowledge, have examined adherence.⁸⁸ Soligard et al.⁹ testing the effect of the 11+ found a 32% reduction of injuries among female youth soccer players. In a secondary analysis comparing players with high compliance (1.5 sessions per week) to players with intermediate compliance (0.7 sessions per week), they found that players with high compliance had a 35% lower injury risk.⁸⁸ Such findings were echoed in data from Canada⁸⁹ as well as by Silvers-Granelli et al.⁸⁸ who found the same pattern in collegiate male soccer players; higher program compliance leads to greater benefit with respect to decreased injury risk and severity of injury.

The Swedish Knäkontroll study found an impressive 64% reduction in ACL injury risk among female youth soccer players.¹⁰ The compliance analyses showed that players with high compliance had significantly reduced ACL injury risk as compared with players with low compliance.¹⁹ *Thus, the relationship between high compliance and reduction of injuries is clear; however, more real-world strategies to improve compliance are needed.*

2.4 | Techniques for enhancing implementation, compliance, and adherence

O'Brien and Finch stated, “To succeed in implementing the prevention exercises we need to understand how coaches, players and team members perceive the programs. Who should be responsible for injury prevention, when should it be performed, (who, when and how?). These questions need to be modified/customized to the sport and age group.”⁹⁰ This quote touches on a progression that could help optimize IPP implementation, compliance, and adherence, *recognizing*

TABLE 1 Definitions of compliance and adherence

Compliance and adherence as defined by McKay and Verhagen⁸⁵

Compliance—“refers to the act of an individual conforming to professional recommendations with regard to prescribed dosage, timing, and frequency of an intervention.”

Adherence—“is a process influenced by the environment, recognizing that behavior is shaped by social contexts as well as personal knowledge, motivation, skills, and resources.”

and taking responsibility, identifying the key stakeholders and the culture, identifying barriers, and strategizing solutions unique to the group.

One successful strategy to bolster adherence is to let the IPP act as a warm-up.⁹¹ Using the ACL IPP as a warm-up relies on high player attendance at training sessions to assure that most players get a “high enough” IPP dose to have a preventive effect⁹²; however, it also bolsters comradery and decreases reliance on individual motivation or behavior. A common complaint from coaches regarding ACL IPPs as warm-ups was that the programs took away valuable or limited training session time. In response, Whalan et al.⁹³ tested rearranging the order of the 11+. The study found that by *simply performing the strengthening portion of the 11+ after the training session (the dynamic stretching and running portions still used as a warm-up), player compliance improved and the number of severe injuries and total injury burden decreased.*⁹³

Several studies have demonstrated an effect of the 11+ on athlete performance.^{94–96} As coaches are key to implementation and compliance, particularly at the youth and nonelite levels, improved performance may act as another attractive message to coaches and players, convincing them to use an IPP regularly. Further, in professional soccer injuries negatively influence the team performance,⁹¹ *thus if reducing injuries and enhancing athletic performance are not enough to earn coach “buy-in,” improved player availability and team performance may.*

Using role models is another way that approaches prevention with both athletes and coaches. An Australian study found that community-level athletes respond to nonelite role models, whereas coaches' role models are a combination of both high-level and nonelite athletes.⁹⁷ Role models that appeal to the coaches' moral obligations to keep the players healthy could be successful in bolstering ACL IPP implementation and adherence.⁹⁷

Compliance/adherence

Clinicians/practitioners

- There is a clear relationship between compliance with effective ACL IPPs and injury reduction.
- Clinicians/practitioners may find that education and discussions with coaches may be helpful in convincing them to implement an ACL IPP. In particular, education on the physiological and performance benefits of ACL IPPs as well as the benefits endowed by greater player availability may be convincing.
- Role models may be beneficial for demonstrating and leading both players and coaches in ACL IPP implementation and compliance.

Researchers

- More information on ACL IPP dosage could allow for an understanding of a minimum dosage needed to achieve injury reduction as well as the dose–response relationship.
- Compliance and program fidelity should be reported in ACL IPP literature.

2.5 | 2019 Novel coronavirus

2019 Novel coronavirus (COVID-19, severe acute respiratory syndrome coronavirus 2) was declared a global pandemic in March 2020.⁹⁸ Due to the circumstances surrounding the COVID-19 pandemic, most countries suspended sport to mitigate the spread of infection, and many athletes found themselves in lockdown, unable to train outside or access gyms/facilities. Lockdown conditions represented a massive obstacle to attaining or maintaining optimal performance and physiological fitness. Suboptimal preparation and fitness are known risk factors for injury,^{99–101} as is match congestion,^{102–104} leading many researchers and clinicians to hypothesize that increased injury rates would occur upon return to sport after COVID-19.^{105–108}

The Bundesliga in Germany was the first major sporting league to return to competition. In the first 3 weeks of matches postlockdown, the injury rate increased threefold, from 0.27 to 0.74 injuries per match.¹⁰⁹ Thus far, only anecdotal reports of increased knee injuries rates exist in young female athletes, but increased numbers of ACL injuries have been reported in the National Football League (NFL).^{110,111} The only comparisons for the COVID-19 lockdown are with unanticipated season breaks such as the player's union strike in the NFL.¹¹² Table 2 describes the ACL injuries in the pre- and regular season in 2011 after a lockout that shortened preseason and the 2020 COVID-19 shortened season. As predicted,^{105–108} higher ACL injury rates have been observed, yet the full physical, psychological, nutritional, and economic implications of the pandemic are still largely unknown.¹¹³

It is critical for the sports medicine community to continue to guide athletes and sporting organizations as they resume training and competition. Balancing finances with the implications on athletes' health is obligatory. For example, scheduling an adequate preseason and avoiding match congestion are two well-supported risk mitigation strategies.^{99–104} Fewer games means less revenue; however, financial viability must be weighed against both the quality and safety of play. Especially for younger and nonelite athletes for whom games are not revenue-generating, leagues/clubs should use meticulous caution in scheduling and planning seasons. After lockdowns, particularly if athletes are limited in their training intensity and volume, athletes may need another, or longer, preseason to rebuild their

TABLE 2 Number of ACL injuries in the NFL seasons around the 2011 Lockout and 2020 COVID-19-affected season^{110,111}

	Preseason/off-season organized team activities (OTA)	Regular season/postseason
2010 (Full season)	64 Games/11 ACL injuries	331 Games/35 ACL injuries
2011 (NFL lockout, limited preseason training)	64 Games/13 ACL injuries	331 Games/35 ACL injuries
2012 (Full season)	64 Games/29 ACL injuries	331 Games/33 ACL injuries
2018 (Full season)	64 Games/13 ACL injuries	331 Games/21 ACL injuries
2019 (Full season)	64 Games/17 ACL injuries	331 Games/32 ACL injuries
2020 (COVID-19, data as of January 3, 2021)	No preseason games/11 ACL injuries	256 Games/41 ACL injuries

Abbreviations: ACL, anterior cruciate ligament; COVID-19, 2019 novel coronavirus; NFL, National Football League; OTA, organized team activities.

chronic loads and prepare them for the intensity of full team training sessions and games. Tournaments or periods of congested matches should not be scheduled until athletes have adequate fitness (both cardiovascular as well as rebuilt strength), with particular attention to young athletes who participate in multiple teams. *Whether via interpreting existing literature to ensure athletes build adequate fitness and physical preparation or explicitly implementing ACL IPPs, clinicians and practitioners must use their clinical reasoning and best judgment, as no precedent and no research-proven techniques exist to reduce ACL injuries after long lay-off periods, such as during COVID-19.*

COVID-19

Clinicians/practitioners

- After a shortened preseason or preparation, athletes are at a higher risk for injury.
- Longer, or a second, preseason helping athletes rebuild their chronic load, and avoiding congested match schedules, may help in reducing athletes' risk.
- Clinicians and practitioners must use their clinical reasoning and best judgment to interpret and extrapolate from the existing literature in building evidence-informed return to play plans for their athletes.

Researchers

- To date, there are no research-backed protocols or programs for returning to sport after long lay-offs, such as lockdown. Post-COVID-19 return to play case

studies and case series will be valuable for sharing successes and failures.

- Although sometimes harder to publish, unsuccessful programs or protocols may be as valuable to the sports medicine community as successful programs.

3 | FUTURE DIRECTIONS

Beyond the areas already discussed, there are other gaps in the ACL IPP literature related to sports, sex, geographical region, race/ethnicity, as well as now the impact of COVID-19.

Much of the ACL IPP research is on soccer.⁴² Some research exists on handball, as well as basketball and volleyball; however, there are other high-risk sports that need attention.¹¹⁴ Approximately 20 million people play netball worldwide.¹¹⁵ Predominantly a women's sport, the sport has a very high ACL injury rate,¹¹⁶ likely due to the rapid decelerations and pivoting. To date, there is only one netball knee injury IPP published.¹¹⁶ Smaller, somewhat more regional, sports with high ACL injury risks but little research also include lacrosse¹¹⁷ and Australian rules football.^{117,118} *Coaches, athletes, and parents should use established programs in similar sports until sport-specific programs are designed and researched.*

Individual sports have also received less attention than team sports. Due to its extremely high ACL injury risk, skiing has had the most ACL IPP research of individual sports.^{119–121} However, sports such as gymnastics¹²² and wrestling^{122,123} also carry high risk for ACL injury and require further prevention work due to their unique demands. There is a sparsity of injury surveillance data on smaller "extreme" sports such as skateboarding, BMX, break dancing, or parkour. Information on the incidence of ACL injuries in such sports will help inform whether prevention programs are needed.

The higher risk for ACL injuries in women^{42,124} has garnered both more attention and research funding. In total numbers, however, more men experience ACL injuries.¹²⁴ One of the first ACL IPPs published was

in men exclusively⁷¹; however, since then there have been comparatively fewer studies of ACL IPPs in men than women.^{11,12,35,125} Thus, more research on programs effective in men as well as if there are differences that tailor programs to each sex is needed.

Sport specialization in young athletes is common. Talented young athletes may play in multiple teams, increasing their training time, match exposure, and injury risk.¹²⁶ While sport specialization research is sometimes focused on overuse injuries,¹²⁷ acute injuries such as ACL injuries, and the long-term impact of prevention strategies requires further investigation.

Owoeye et al.¹¹ examined the efficacy of the 11+ program in young Nigerian men. To date, their study remains one of the few ACL IPP studies not to be conducted in North America, Europe, or Australia.^{86,128,129} Multiple meta-analyses of ACL-IPPs have included only studies from the United States and Europe.^{128,129} Such lack of diversity in study location would suggest also a lack of ethnic diversity in the study populations; however, given a lack of reporting guidelines/requirements for publication, it is impossible to know. Recently, Dr. Tracy Blake wrote a powerful article¹³⁰ calling on researchers worldwide to use culturally competent research practices and both reporting and discussing the relevant biases and generalizability. ACL IPP research must heed these calls as well as improve regional investigations on knowledge, behavior, implementation, such as Owoeye et al.¹³¹ in Nigeria.

Future directions

Clinicians/practitioners

- Clinicians, coaches, parents, and athletes in under-researched high ACL risk sports with similar movement patterns should use established ACL IPPs until sport-specific programs can be established and researched.
- For example, given the similarities between women's lacrosse and soccer, the 11+ program may be beneficial for lacrosse players until lacrosse-specific programs are available.
- Clinicians, coaches, parents, and athletes working in under-researched areas should work with their communities to identify the unique ACL IPP barriers and facilitators strategizing community-oriented solutions and sharing successes and failures with the wider sports medicine community.
- Clinicians/practitioners should take the time to investigate the disparities in health care, sports medicine, and injury

prevention access in their own communities. Becoming an ally¹³² is a powerful step in reducing disadvantages.

Researchers

- More research is needed in high-risk team sports, such as Netball, lacrosse, and Australian rules football, as well as individual sports, such as gymnastics and wrestling.
- There are indications that men and women may respond to ACL IPPs differently. Thus, research into tailored programmatic differences for each sex as well as effective programs for men is needed.

Research on ACL IPPs should not be limited to the United States, Australia, and Europe. Greater diversity in both the study locations and populations is necessary. Further, culturally competent research methods must be followed in ACL IPP publications.

4 | CONCLUSION

There has been significant progress in ACL IPP research over the past 30 years. ACL injuries can be reduced across sports, particularly in young women.⁴² Exercise-based programs, often used as warm-ups, are effective, but their success depends on implementation and compliance.^{19,75,88} Thus, researchers and clinicians must collaborate with coaches, athletes, parents, and other stakeholders to help identify barriers and strategies. Sports that lack researched ACL IPPs, particularly sports with movement patterns similar to soccer or handball, can use existing ACL IPPs until sport-specific research is available. Further research is needed into understanding both the risk factors that contribute to ACL injuries and the mechanism by which ACL IPPs are effective. Newer evidence indicates that the mechanism of ACL IPPs could be in changing brain-behavior using motor learning principles.^{52,53,133} However, the future holds a need for further research. Whether it is research into understudied sports and geographical regions, or subtleties between how men and women respond to ACL IPPs, the next 30 years of ACL injury prevention research will be enlightening and exciting.

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