Connecting Physical Literacy and Injury Prevention Strategies: Assessing and Intervening Movement Skills in 8-12-Year-Old Children

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ABSTRACT

Connecting Physical Literacy and Injury Prevention Strategies: Assessing and Intervening Movement Skills in 8-12-Year-Old Children

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Concordia University, 2023

Physical activity is associated with positive health outcomes in children and adolescents. The physical literacy model aims to promote lifelong physical activity by focusing on affective, cognitive, behavioral, and physical factors. Promoting physical activity in youth is a global objective; however, participating in physical activity and sports is associated with an increased risk of lower-limb musculoskeletal injuries, which is a barrier to physical activity participation. Injury prevention strategies use multicomponent injury prevention programs and screening tools that target modifiable risk factors of injury. The physical literacy model and injury prevention strategies use similar movement-related constructs but are rarely connected in the literature and practice. A screening tool that assesses movement competence and injury risk may be a valuable source of information to fit interventions in different contexts. An intervention based on the physical literacy model and multicomponent injury prevention programs may help enhance physical literacy constructs and neuromuscular performance and reduce the risk of lower-limb injuries. Addressing these related elements and constructs may favor adopting and maintaining physical activity. This dissertation consists of five chapters. Chapter one introduces the concepts used in the dissertation and states the hypotheses and objectives. Chapter two describes a systematic review with six meta-analyses that studied the characteristics and effects of multicomponent injury prevention programs on various fundamental movement skills in children and adolescents. Chapter three describes the evaluation of the concurrent and construct validity

of the Children Focused Injury Risk Screening Tool (ChildFIRST). The ChildFIRST is a process-based assessment of movement skills that aims to identify 8-12-year-old children with poor movement competence and increased risk of lower-limb musculoskeletal injury. Chapter four was based on the evidence from the second chapter and the literature, and it describes the development, implementation, and feasibility testing of a neuromuscular warm-up for 8-12-year-old children. The neuromuscular warm-up was based on the physical literacy model and multicomponent injury prevention programs. The intervention positively affected physical literacy constructs, neuromuscular performance, movement competence, and injury risk profile, which was assessed using the ChildFIRST. Chapter five discusses the findings from chapters two, three, and four and offers a general conclusion and recommendations for future research.

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CONTRIBUTIONS OF AUTHORS

This dissertation consists of three articles. In the first article (chapter two), Dr. Matthew Miller contributed to the writing and was the second reviewer for the systematic review and meta-analysis. In the second article (chapter three), Chanelle Montpetit contributed to the recruitment, data collection, and writing processes of the validation study. In the third article (chapter four), Alejandro Gómez-Rodas contributed to the recruitment of participants and volunteers, data collection, and editing process of the cluster non-randomized controlled trial.

Dr. Richard DeMont, as my supervisor, contributed significantly to the inception, design, data collection, analysis, revision, and editing of all articles in this dissertation. I was the lead researcher for all articles. I designed the studies, planned the statistical analyses, recruited the participants, collected the data, analyzed the results, and wrote the articles. Article two was funded by PERFORM Centre through the Graduate Scholarship in Preventative Health Research. Article three was funded by Concordia University and The *Gouvernement du Quebéc* through the Quebec's Mobility bursary, allowing me to collect data in Colombia. I was personally funded by Concordia University through the Faculty of Arts and Science Doctoral Fellowship.

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Chapter One: Introduction

1.1 General Introduction

Children are not "mini-adults" and assessing and intervening any childhood-related construct involve complex processes, particularly as individuals transition from childhood and adolescence into adulthood.[1] During the ages between 8 and 12, children experience several changes that are regulated by growth and maturation processes that directly affect their movement competence, risk of suffering musculoskeletal injuries, and participation in physical activity (PA) and sports.

The World Health Organization (WHO) defines PA as any bodily movement produced by the musculoskeletal system that requires energy expenditure.[2] PA is an essential aspect of children's overall health and wellbeing; for instance, mental, metabolic, musculoskeletal, immunologic, and cardiovascular health are all influenced by PA.[2,3] PA is also key for maintaining a healthy weight status by reducing the risk of overweight and obesity.[1] Public health institutions and stakeholders recommend that children and adolescents should engage in moderate-to-vigorous PA (MVPA) at minimum of 60 minutes per day.[2,4] The recommended 60 minutes should include vigorous-intensity aerobic activities and activities that strengthen the musculoskeletal system.[2,4]

More than 80% of individuals aged between 11 and 17 years worldwide did not meet the recommended daily PA levels in 2016.[2] The residual effects of physical inactivity, sedentary behavior, and prolonged screen time in youth can lead to a lifetime of preventable diseases and conditions, such as cardiometabolic diseases, different types of cancer, and overweight or obesity.[2,5,6] In 2016, over 340 million of children and adolescents aged 5-19 globally were living with overweight or obesity.[6] The incidence of overweight and obesity among children and adolescents has risen sharply, from 4% in 1975 to 18% in 2016.[6] Physical inactivity may stem from the interplay between physical illiteracy, exercise deficit disorder, and pediatric dynapenia.[5] Physical illiteracy refers to individuals who lack movement competence, confidence, motivation, and knowledge to value and take responsibility for engagement in lifelong PA.[7] Exercise deficit disorder is a condition in which individuals do not meet the recommended daily levels of MVPA.[2,5] Pediatric dynapenia is characterized by diminished muscular strength and power, leading to functional limitations that are not caused by neurological or musculoskeletal conditions.[5]

Promoting PA in youth is fundamental to prevent chronic diseases and conditions that can affect the quality of life during childhood and adolescence and carry over into adulthood.[1] Significant resources have been invested in research, development, and implementation of various strategies to promote PA.[4,8,9] These strategies are not always effective as many barriers (e.g., socioeconomic, cultural, environmental) to PA exist.[9–11] Given the challenging nature of addressing all barriers to PA participation, various models and frameworks have been proposed to guide PA promotion.[3,7]

The physical literacy model proposed by Whitehead in 2001 is a response to the declining PA rates in youth and aims to promote lifelong PA by considering a comprehensive philosophical foundation and targeting affective, cognitive, physical, and behavioral domains.[7,12] The four domains of physical literacy are the affective (e.g., confidence and motivation), cognitive (e.g., knowledge and understanding), physical (e.g., movement competence and physical fitness), and Behavioral (e.g., responsibility to engage in actual PA).[7] The physical literacy domains are complementary and interconnected conforming a holistic model that strongly target human development.[12–14] The physical literacy model is an important element of physical education (PE) curricula, public policies, and the long term athlete development model (LTAD).[14–17]

Physical literacy interventions are normally movement-based with a strong focus on the enjoyment and interaction with peers and the environment through developmentally appropriate games and activities.[8,13,14] Movement competence is a construct of the physical domain of the physical literacy model and refers to goal-oriented proficiency in any movement-based activity, including the underlying processes of movement such as coordination and control.[3] Children with enhanced movement competence are more likely to engage with PA, and PA is hypothesised to promote further development of movement competence.[3] Fundamental movement skills are normally used to operationalize movement competence.[18] Fundamental movement skills are the foundation for more complex movement skills and are essential for completing everyday activities and engage in PA and sports.[19] Fundamental movement skills are classified as object control skills (e.g., kicking, throwing, dribbling), locomotor skills (e.g., running, jumping, single-leg hop), and balance skills.[4,5]

Movement competence assessment tools aim to assess the degree of proficiency in performing a wide array of fundamental movement skills.[18] Movement competence assessment tools can be categorized as either process-based, product-based, or a combination of both.[20,21] Process-based assessment tools assess the quality of the movement (e.g., body position, posture, joint alignment, coordination).[20] Product-based assessment tools focus on quantitative outcomes of the movement (e.g., time to complete a task, distance).[20] The assessment of basic human movements complement the assessment of movement competence to understand individuals' movement behaviour.[22] Basic human movements, such as pulling, pushing, squatting, and lunging, are critical movement patterns that enable individuals to interact with the environment and directly influence children's and adolescent's movement competence.[22]

Assessing and intervening movement competence is essential due to its association with PA and its relevance in the physical literacy model. Moreover, PA has several benefits that contribute towards positive health trajectories, supporting any effort and investment for its promotion. However, participating in PA and/or any movement-based activities have inherent risks that cannot be ignored and can lead to unfortunate events that negatively impact children's lives.[23] PAs that include jumping, landing, running, and cutting increase the risk of suffering musculoskeletal injuries.[24–26] Injuries can result from a series of changing circumstances occurring together, in which risk factors play a crucial role in a dynamic cycle.[27] A musculoskeletal injury can be defined as any physical state that hinders movement and affects the musculoskeletal system, regardless of the need for medical attention or time away from activity.[28] Injuries have both direct economic costs associated with evaluation, treatment, and rehabilitation, and indirect costs when parents alter their own activities to attend to an injured child.[29] In many countries, PA-related injuries are one of the most significant hazards for school-aged individuals, with sports and leisure activities accounting for at least 39% of fractures in children and adolescents.[30,31] Children may be more prone to musculoskeletal injury due to physiological and physical factors such as growth spurts, maturity status, imbalances between strength and flexibility, structural laxity, and lack of motor and cognitive skills required for specific activities.[29,32] While musculoskeletal injuries typically do not result in in permanent disability, children who experience PA-related musculoskeletal injuries may undergo traumatic events including medical attention, surgery, and acute and chronic pain that can significantly impact their daily lives.[1,30]

Lower-limb musculoskeletal injuries (e.g., anterior cruciate ligament tears, ankle sprains) constitute 66% of all sport-related injuries and may lead to other musculoskeletal conditions (e.g., early onset of knee osteoarthritis), predisposition to re-occurrence, prolonged school absences, contribute to the childhood obesity epidemic, and hinder participation in PA and organized sports.[1,28,29,33] The negative perception and fear of injury may lead to decreased confidence, motivation, and willingness to engage in PA during the childhood.[34]

Stakeholders have developed, validated, and implemented various injury prevention strategies because musculoskeletal injuries can be a barrier to participating in PA and sports, impose a burden on health systems, and determine children's health trajectories.[1,27] Injury prevention strategies include screening tools and multicomponent injury prevention programs (MIPP). The process of injury screening involve a systematic observation of an individual's movement patterns, range of motion, joint alignment, strength, posture, and balance/stability.[35] Screening tools are used in healthy, uninjured, individuals to identify potential risk factors that could lead to future musculoskeletal injuries.[36] Screening tools synthesizes biomechanical, neuromuscular, and/or movement competence observations to objective metrics.[37] Identifying limitations in biomechanics, neuromuscular function, and movement competence that contribute to poor movement patterns is necessary to direct targeted and corrective strategies in different contexts.[38] Researchers and practitioners developed, validated, implemented, and evaluated MIPP with the aims to reduce musculoskeletal injury risk and enhance neuromuscular performance and health- and skill-related fitness.[39] MIPP are exercise-based interventions that focus on strength, plyometrics, agility, balance, and flexibility while controlling for proper technique.[33]

Rationale

The physical literacy model aims to holistically promote PA as a response to the declining PA levels in youth, which may lead to chronic diseases and are associated with negative health trajectories.[7] While promoting PA is a global objective and its benefits outweighs the risks, engaging in PA and sports is associated with an increased risk of suffering musculoskeletal injuries.[1,28] Lower-limb musculoskeletal injuries can lead to acute pain, long-term chronic diseases and conditions, prolonged physical inactivity periods, and decreased confidence and willingness to participate in PA and sports.[35,38,40] Injury prevention strategies include injury screening tools and MIPP and target various risk factors to reduce musculoskeletal injury rates.[28]

Movement competence is considered as an internal modifiable risk factor for musculoskeletal injuries, which highlights its importance for both physical literacy and injury prevention fields.[41] While systematic frameworks in sports-related settings (e.g., soccer, volleyball, rugby) typically include MIPP, movement-based processes like physical literacy interventions and PE classes, where movement competence is key, often omit injury prevention strategies.[24,42] Considering that promoting PA is essential, the risk of suffering musculoskeletal injuries associated with PA participation reveals the need of injury prevention efforts to promote safe PA in youth.[25,43]

In a previous literature review (2018), our research team proposed a connection between physical literacy and injury prevention strategies through the assessment of fundamental movement skills and basic human movements.[24] Fundamental movement skills and basic human movements are: (1) used in movement competence assessment tools and injury prevention screening tools; and (2) used in movement-based physical literacy interventions and MIPP.

Although the physical literacy model and injury prevention strategies use similar movement-related constructs and focus on comparable physiological and biomechanical factors, they are rarely connected in the scientific literature and practice.[24] Connecting the physical domain of the physical literacy model and injury prevention strategies (Figure 1)through the assessment and intervention of movement skills may have positive effects on physical literacy constructs and musculoskeletal injury risk profile to promote safe lifelong PA in 8-12-yearl old children.

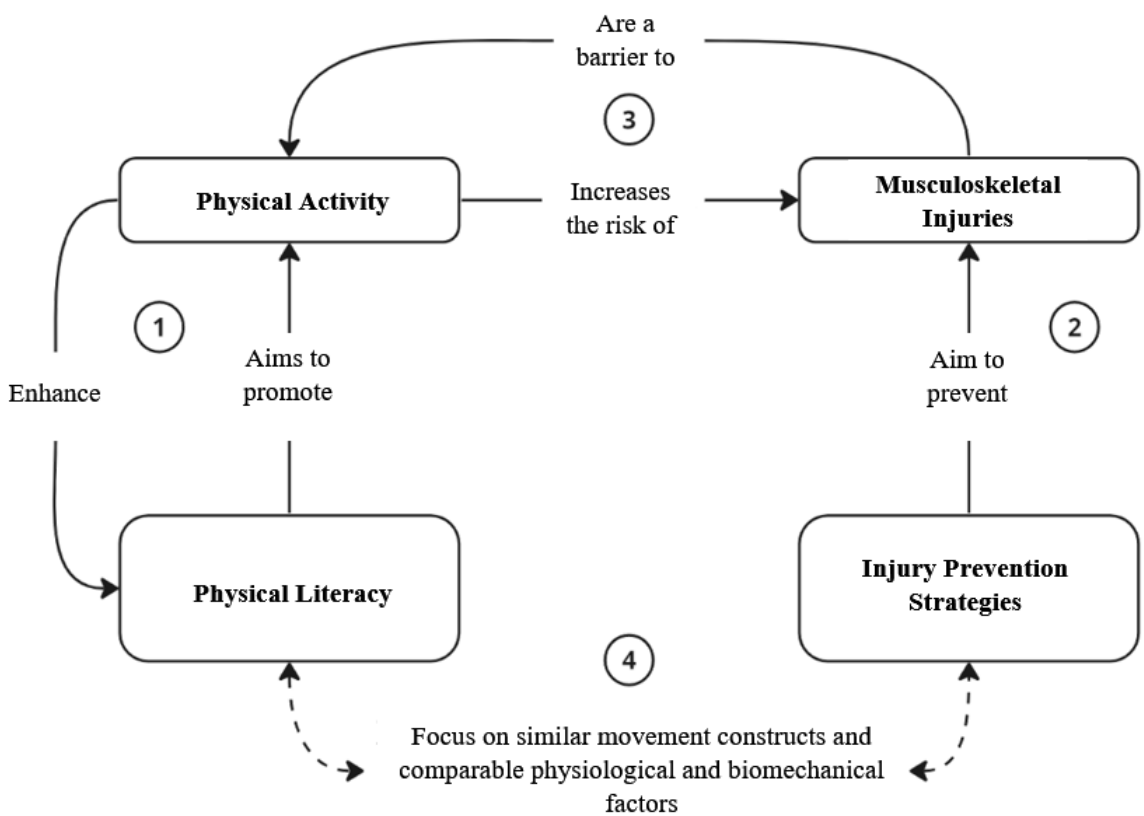

Figure 1. Rationale Diagram. (1) Positive relationship between physical literacy and physical activity. (2) Positive relationship between injury prevention strategies and musculoskeletal injuries. (3) Negative relationship between physical activity and musculoskeletal injuries. (4) Potential relationship between physical literacy and injury prevention strategies.

Chapters two, three, and four aim to bridge the gap between the physical domain of the physical literacy model and injury prevention strategies. Chapter two is a systematic review with meta-analyses of randomized controlled trials published in the *American Journal of Health Promotion*.[44] We studied the characteristics of MIPP and their effects on biomechanical outcomes and neuromuscular performance measured in children and adolescents while doing fundamental movement skills. Chapter two was the foundation to develop a neuromuscular warm-up. Chapter three describes the testing of the construct and concurrent validity of the Children Focused Injury Screening Tool (ChildFIRST). The ChildFIRST target 8-12-year-old children and consists of ten movement skills, each with four evaluation criteria. We developed the ChildFIRST at the Athletic Therapy Research Laboratory at Concordia University and previously tested its face and content validity and intra- and inter-rater reliability;[45,46] however further validity evidence was warranted. We compared the ChildFIRST against three-dimensional (3D) motion analysis, the Test of Gross Motor Development 3 (TGMD-3), and the modified version of the Star Excursion Balance Test (mSEBT). The results reported in chapter three helped to validate the ChildFIRST to evaluate the effects of the neuromuscular warm-up by assessing movement competence and musculoskeletal injury risk profile in 8-12-year-old children. The paper submission developed as chapter three is currently under review in *Measurement in Physical Education and Exercise Science*. Chapter four focused on the development, implementation, evaluation, and feasibility testing of a neuromuscular warm-up based on the physical literacy model and MIPP. The intervention aimed to improve outcomes related to increased PA levels (i.e., physical literacy constructs), enhanced neuromuscular performance and movement competence, and reduced risk of lower-limb musculoskeletal injuries in 8-12-year-old children.

1.2 Research Objectives & Hypothesis

This dissertation explores the connection between the physical domain of the physical literacy model and injury prevention strategies through the assessment and intervention of movement skills. The overarching goals of this dissertation were: (1) to develop and implement a neuromuscular warm-up based on the physical literacy model and injury prevention strategies for 8-12-year-old children; and (2) to validate the ChildFIRST to assess movement skills in 8-12-year-old children. Chapters two, three, and four helped to achieve the overarching goals based on the following objectives and hypotheses:

Chapter Two Objective

- To synthesize the evidence on the effects of MIPP on biomechanical outcomes and neuromuscular performance measured on children and adolescents while performing fundamental movement skills.

Chapter Two Hypothesis

- MIPP have positive effects on biomechanical outcomes and neuromuscular performance measured on children and adolescents while performing fundamental movement skills.

Chapter Three Objective

- To test the concurrent and convergent validity of the ChildFIRST by comparing it against 3D motion analysis, the TGMD-3, and the mSEBT.

Chapter Three Hypothesis

- The ChildFIRST has concurrent and convergent validity.

Chapter Four Objectives

- To test the feasibility of the neuromuscular warm-up and assessment protocol for 8-12-year-old children in a school setting.

- To explore the effects of the neuromuscular warm-up in physical literacy constructs (i.e., affective, cognitive, physical), neuromuscular performance, and musculoskeletal injury risk profile in 8-12-year-old children.

Chapter Four Hypotheses

- The neuromuscular warm-up and assessment protocol meet the feasibility criteria.
- The neuromuscular warm-up has positive effects on physical literacy constructs, neuromuscular performance, and musculoskeletal injury risk profile in 8-12-year-old children.

Chapter Two: Manuscript One

Effects of Multicomponent Injury Prevention Programs on Children and Adolescents' Fundamental Movement Skills: A Systematic Review with Meta-Analyses

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Effects of Multicomponent Injury Prevention Programs on Children and Adolescents' Fundamental Movement Skills: A Systematic Review With Meta-Analyses

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Abstract

Objective: Fundamental movement skills (FMS) are essential to participate in physical activity. Understanding the effects of multicomponent injury prevention programs (MIPP) on FMS may help promote safe physical activity. Our objective was to synthesize the evidence on the effects of MIPP on biomechanical outcomes and neuromuscular performance measured on children and adolescents while performing FMS.

Data Source: We searched PubMed, SPORTDiscus, Web of Science, and SCOPUS.

Study Inclusion and Exclusion Criteria: We included peer-reviewed randomized controlled trials, published in English, that analyzed the effects of MIPP on biomechanics and neuromuscular performance of FMS in participants under 18 years of age.

Data Extraction: Two reviewers screened the articles, assessed the quality of the evidence using the Physiotherapy Evidence Database (PEDro) scale, and synthesized the data.

Data Synthesis: We conducted meta-analyses and reported the characteristics, outcomes, and risk of bias of studies.

Results: We included 27 articles that reported data from 1,427 participants. Positive effects on FMS were reported in 23 of the 27 included articles. Vertical Jump, running speed, acceleration, and dynamic balance presented positive-significant pooled effect sizes. Dribbling and horizontal jump presented non-significant pooled effect sizes.

Conclusion: MIPP can positively affect FMS in children and adolescents in sports-related settings. Lack of participant compliance and implementation fidelity may affect MIPP effectiveness. Including MIPP in physical literacy interventions, physical education classes, and organized physical activity may lead to functional adaptations that help promote safe physical activity.

Keywords

injury prevention, physical activity, fundamental movement skills, youth, physical literacy

Introduction

High rates of physical inactivity are associated with increased weight status and poor health- and skill-related fitness.[1] The residual effects of physical inactivity during childhood and adolescence can lead to preventable chronic conditions, such as depression and metabolic and cardiovascular diseases, which increase the risk of all-cause mortality.[1,2] Globally, more than 80% of 11–17-year-old individuals did not meet the recommended daily physical activity levels, and over 340 million of 5–19-year-old individuals were overweight or obese in 2016.[1] The prevalence of overweight and obesity among children and adolescents increased from 4% in 1975 to 18% in 2016.[3]

Physical activity promotion efforts aim to decrease pediatric physical inactivity and sedentary behaviour; for instance, the physical literacy model promotes lifelong physical activity by targeting affective (eg, confidence, motivation), cognitive (eg, knowledge, understanding), physical (eg, movement

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competence), and behavioral (eg, sedentary behavior) factors.[4] Promoting physical activity is a global objective, yet epidemiological data and injury aetiology models suggest that regular physical activity is associated with an increased risk of musculoskeletal injuries.[5,6] Musculoskeletal injuries may lead to physical inactivity and chronic musculoskeletal conditions, which further hinder participation in physical activity.[7] Musculoskeletal injuries have direct economic costs from evaluation, treatment, and rehabilitation and indirect costs when parents are required to attend to an injured child.[8] Physical activity-related injuries are one of the most important threats to school-aged children and adolescents, and sports and leisure activities were associated with at least 39% of fractures in these populations.[9,10] The injury risk associated with physical activity reveals the necessity of injury prevention efforts to promote safe physical activity.[11]

Multicomponent injury prevention programs (MIPP) were developed to reduce injury risk and enhance health- and skill-related fitness.[12] We used MIPP as an umbrella term to generalize standardized injury prevention programs and multicomponent neuromuscular training. When implementing MIPP, researchers and practitioners provide feedback on the exercise technique targeting at least three of the following components: strength, plyometrics, agility, balance, and flexibility.[7] Systematic frameworks in sports-related settings typically include MIPP; however, physical literacy interventions, physical education curricula, and organized physical activity often omit injury prevention strategies.[13,14]

Fundamental movement skills (FMS) are commonly used in MIPP and play a significant role in physical literacy interventions, physical education, and organized physical activity.[4,15] FMS are the foundation of specialized movement skills and are classified as locomotion skills (eg, running, jumping), balance skills (eg, static and dynamic balance), and object control skills (eg, kicking, dribbling).[16] Individuals who do not address FMS deficiencies early in life may be unmotivated and lack the skill to engage in lifelong physical activity and sports, and may also be at an increased risk of musculoskeletal injury.[2,17] Targeted FMS are used in movement competence and physical literacy assessments as well as injury prevention screening tools.[14] Previous research proposed a connection between physical literacy and MIPP through the assessment of FMS.[14]

Public health strategies and physical education curricula may benefit from incorporating improved knowledge of the effects of MIPP on FMS in children and adolescents.[18] MIPP can incorporate developmentally appropriate exercises to improve physical fitness and may lead to engagement in PA through increased confidence and motivation.[2,4] Other systematic reviews and meta-analyses focused on the effects of MIPP on neuromuscular performance and biomechanical outcomes in children and adolescents,[15,19,20] but these studies are missing a specific focus on the effects of MIPP on FMS. Our objective was to synthesize the evidence on the effects of MIPP on biomechanical outcomes and neuromuscular performance measured on children and adolescents while performing FMS.

Methods

We used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement to report this systematic review with meta-analysis.[21]

Data Sources

We systematically searched PubMed [Medline], SPORTDiscus, Web of Science, and SCOPUS from their inception until July 1st, 2022. We developed a search strategy using the PICOS (Population, Intervention, Comparison, Outcome, Study design) approach and a combination of search terms, synonyms, truncation, and Boolean conjunctions. We then performed citation tracking of key articles, review articles, and authors' bibliographies to find relevant studies not identified using the search strategy. Search term combinations can be found in the Supplementary Content.

Inclusion and Exclusion Criteria

We included studies that: (1) included injury-free participants, younger than 18 years of age; (2) implemented at least one intervention incorporating a MIPP; without limits on frequency or duration; (3) used a control group performing either a standard training/warm-up program, sham intervention, or no-treatment; (4) investigated at least one biomechanical outcome and/or neuromuscular performance measured on any FMS; (5) were designed as either a randomized controlled trial (RCT) or a cluster-RCT.

We excluded studies that: (1) included participants who were currently injured or live with a systemic or neurological disease or disability; (2) used an intervention without an injury prevention focus; (3) used a control group performing another exercise-based injury prevention strategy outside their common training routine; (4) did not investigate outcomes measured on FMS; (5) were unavailable or not published in English, and the publication type was an abstract or presentation.

Data Extraction

Two researchers independently screened titles and abstracts. We removed duplicates and obtained full texts if at least one researcher indicated that the article should be included. Then, the researchers screened full texts and made final inclusion/exclusion decisions. In case of disagreement between the researchers, we consulted a third researcher to achieve consensus to make inclusion/exclusion decisions. One researcher extracted all data, and the second researcher did random data-checks as part of the quality control of the study. We used Rayyan QCRI to manage the search,[22] Zotero (Corporation for

Digital Scholarship, 2020) to manage the references, and a spreadsheet to record the data and decisions. We extracted relevant study information, including authors, year, sample characteristics, outcomes, and intervention and control characteristics. We estimated the level of agreement between researchers in the data extraction process using the Intraclass Correlation coefficient (ICC).

Risk of Bias Assessment of Individual Studies

Two researchers used the Physiotherapy Evidence Database (PEDro) scale to assess the quality of evidence of included articles independently. The PEDro scale has validity and reliability evidence to assess the quality of RCTs.[23] Although the PEDro scale uses 11 dichotomous criteria (Yes or No), criterion 1 is not included in the total PEDro score because it pertains to external validity.[23] Lower values in the PEDro scale indicate potential bias, while higher values in the scale are indicators of high methodological quality.[23] The researchers were not blinded to the relevant content of the studies (eg, authors' names). In case of disagreement between the researchers, we consulted a third researcher to achieve consensus on PEDro scores. We estimated the level of agreement between researchers in the quality assessment using the ICC. We did not exclude any study based on the risk of bias assessment.

Synthesis of Results

Narrative synthesis. We synthesized the characteristics of the participants, interventions, and outcomes. We investigated outcomes related to the three FMS categories: locomotion, balance, and object manipulation skills.[16] The main outcomes were: (1) biomechanical characteristics (eg, joint angles and moments, postural stability) measured on any FMS, and (2) neuromuscular performance (eg, jump height, running speed) measured on any FMS.

We extracted pre- and post-intervention means and standard deviations (SD) from each outcome. If authors reported more than one outcome on the same FMS category in individual studies, we used the following criteria for statistical analyses: (1) If two outcomes were similar (eg, vertical jump with arms and without arms), we used the outcome showing the smaller effect to have a conservative estimate. (2) If three or more outcomes were similar (eg, three reaching directions for Y-balance test without composite score), we used the outcome showing the medium effect.[15] When data were only available in figures, we extracted the data using an open-source software (Plot Digitizer, http://plotdigitizer.sourceforge.net/).[24]

Meta-analyses. We used R 4.0.3 (https://www.r-project.org/) and the package meta to conduct all statistical analyses.[25] We used an inverse-variance with random-effects model assuming that included studies were methodologically different.[26] We used the DerSimonian and Laird estimator to pool effect sizes and estimate between-study-variance (τ^2). We performed meta-analyses when five or more studies reported the same outcomes to achieve reasonable power for a random-effects model.[27]

We estimated bias-adjusted standardized mean differences (Hedge's g) of the change scores with 95% confidence intervals (CI) and an alpha level of .05. We symbolized effects in favor of the intervention group with a plus (+) sign and created forest plots with 95% CI to graphically summarize the meta-analyses. We estimated and reported statistical heterogeneity using Cochrane Q and quantified it using I^2 statistic; 25%, 50%, and 75% reflect low, moderate, and high heterogeneity, respectively.[28] To assess the risk of a potential publication bias, we created funnel plots and performed Egger's regression tests with a .05 alpha level. Funnel plots can be found in the Supplementary Content.

Results

Search Results

We found 28,427 articles (Table 1) using the search strategy. We identified 1593 potentially relevant articles through title screening and 14 articles using other resources. After removing duplicates and screening titles, abstracts, and full texts, we used 27 articles (Figure 1), representing 26 studies. The agreement between the researchers in the data extraction process was excellent, ICC = .953 95% CI [.914, .992].

Risk of Bias of Individual Studies

We reported PEDro scores for each study in Table 2 and PEDro detailed results in the Supplementary Content. PEDro scores ranged from four to eight. Nine articles obtained scores above or equal to seven in the PEDro scale,[18,29-36] and 18 articles scored under seven in the PEDro scale.[37-54] The agreement between the researchers when using the PEDro scale was excellent, ICC = .941 95% CI: [.906, 0.976].

Table 1. Records Identified by Search Strategy and Title Screening.

Database	Records identified using the search strategy	Records identify through title screening
PubMed	8395	443
Scopus	10851	494
Web of science	6245	371
SPORTDiscus	2936	285
Total	28427	1593

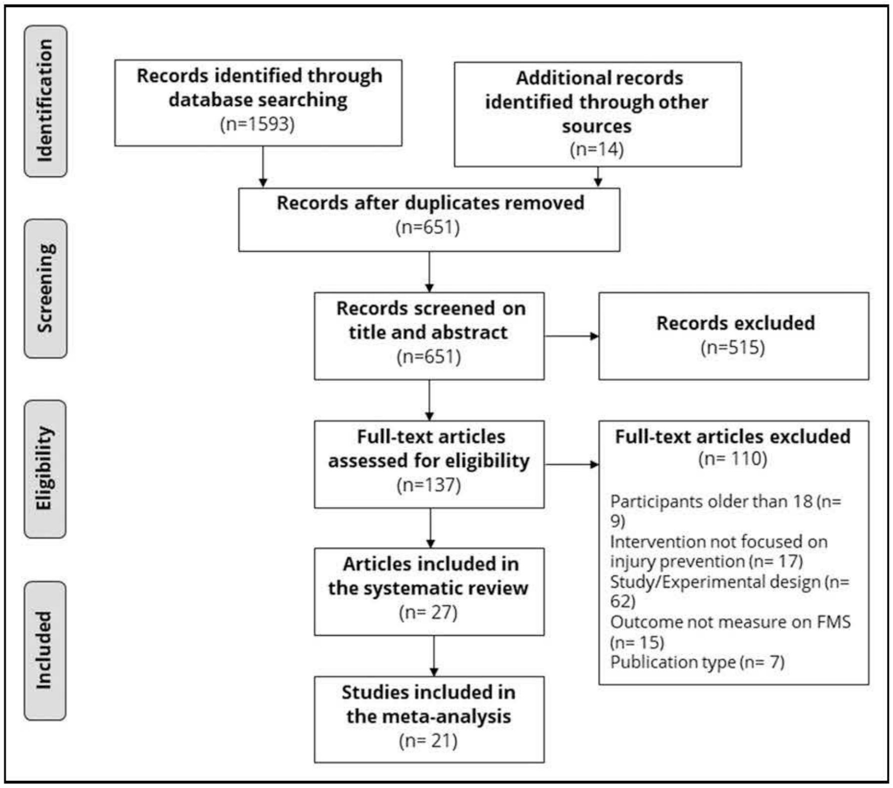

Figure 1. The preferred reporting items for systematic reviews with meta-analysis (PRISMA) flowchart.

Characteristics of Included Interventions and Participants

We reported detailed information for each article in Table 2. Included articles involved 1427 participants of which 715 received an intervention and 49.3% were females (n = 703). The participants' median age was 13.72 years, ranging 7.39–17.30. Ten articles reported data on females only,[18,30,31,39,43,44,46,48-50] 14 articles on males only,[29,32,34,35,37,38,41,42,45,47,51,52] and three articles on both females and males.[33,40] Fourteen articles analyzed participants younger than 14 years,[30-34,40-42,44,46,49,52] and 13 articles analyzed participants older than 14 years.[18,29,35,37-39,43,45,47,48,50,51]

All interventions combined at least three of the following components: strength, flexibility, plyometrics, balance, and agility. Fifty-six percent of the interventions were 6–10 weeks in length, 88.9% of the interventions had 2-3 sessions per week, and 70.37% of the sessions lasted 11–20 min. Twenty-five articles used MIPP as warm-ups and made comparison to regular warm-ups at different sports settings.[18,29-38,40-48,50-54] Two studies used MIPP as part of a session after warming up and made comparisons to a no-treatment conditions.[39,49] Fourteen articles reported a version of the Fédération Internationale de Football Association (FIFA) 11+ (ie "11", FIFA 11+, FIFA 11 + Kids),[29,31,32,34,37,38,41,42,46-48,51,52,54] six articles reported neuromuscular training,[30,35,39,45,49,53] three articles reported anterior cruciate ligament (ACL) injury prevention programs,[18,33,40] three articles reported different versions of standardized IPP (ie, Preventing Injury Enhancing Performance, Netball Dynamic Warm-up, and Harmoknee),[44,46,50] and one article reported an original IPP or cricket.[36] From the 27 articles, one article compared the FIFA 11+ and the Harmoknee program against control groups.[29] Sixteen articles reported data on soccer players,[29-32,34,37,38,40-42,46,48,50-52,54] three articles on basketball players,[18,43,45] seven articles on other sports (ie, field hockey, volleyball, futsal, netball, cricket),[33,35,36,39,44,47,49] and one article on an school-based setting.[53] Nineteen articles were RCT,[29,32,33,35,38,39,41-43,45-50,52-54] and eight articles were cluster-RCT.[18,30,31,34,36,40,44,51]

Outcome Measures

Included articles reported outcomes on all FMS categories (Table 2). Ten articles reported outcomes on locomotion skills,[18,30,33,37-39,42,43,50,54] three articles on balance skills,[35,36,45] seven articles on locomotion and balance skills,[29,31,40,41,44,46,49] two articles on locomotion and object manipulation,[48,51] and five articles on the three FMS categories.[32,34,47,51,53] Regarding the type of outcomes, eight articles reported outcomes on neuromuscular performance,[29,32,36,37,42,46,47,50] seven articles on biomechanics,[18,30,38,39,45,52,54] ten articles on both neuromuscular performance and biomechanics,[31,33-35,40,41,43,44,48,51] and two articles on neuromuscular performance and movement competence.[49,53]

Table 2. Summary of Studies.

Study; Publication Date; Country	Design	Participants (n); Age (years)[a]; Sex (% Female)	Intervention	Duration of intervention; frequency; duration of session	FMS-related outcomes	PEDro score
Kilding et al.; 2008; New Zealand	RCT	24 soccer players; INT: 12; CON: 12; age INT and CON 10.4 (1.4); 0%	INT1: FIFA 11 (modified); CON: No intervention	6 weeks; 5 times per week; 20 min	Countermovement jump; 20 m sprint	6
Steffen et al.; 2008; Norway	RCT	31 soccer players; INT: 17; CON: 14; age INT and CON 17.1 (0.8); 100%	INT: FIFA 11; CON: No intervention	10 weeks; 3 times per week; 15 min	Countermovement jump; 40 m sprint; Slalom dribbling test; Shooting distance	6
Lim et al.; 2009; Korea	RCT	22 basketball players; INT: 11, age 16.2 (1.2); CON: 11, age 16.1 (1.0); 100%	INT: PEP (modified); CON: No intervention	8 weeks; Frequency NA; 20 min	Countermovement jump	6
DiStefano et al.; 2010; United States	Cluster-RCT	65 soccer players; INT1: 19, age 10 (1); INT2: 22, age 10 (1); CON: 24, age 10 (1); 43%	INT1: Progressive pediatric ACL IPP; INT2: Traditional ACL IPP; Control: No intervention	9 weeks; 3 times per week; 12–14 min	Countermovement jump; Time-to-stabilization	6
Vescovi & VanHeest; 2010; United States	RCT	31 soccer players; INT: 15, age 15.7 (1.2); CON: 16, age 16.8 (0.4); 100%	INT: PEP; CON: No intervention	12 weeks; 3 times per week; 15–20 min	9.1 m, 18.3 m, 27.4 m, and 36.6 m Sprint; Countermovement jump	5
Reis et al.; 2013; Portugal	RCT	36 futsal players; INT: 18; CON: 18; age INT and CON 17.3 (0.7); 0%	INT: FIFA 11+; CON: No intervention	12 weeks; 2 times per week; 15–20 min	5 m and 30 m sprint; Slalom dribbling test; Squat jump; Countermovement jump; Single-leg flamingo test	5
Brown et al.; 2014; United States	RCT	23 athletes - teams that require dynamic landings; INT1: 10, age 14.1 (1.2); CON: 13, age 14.7 (2.6); 100%	INT1: Progressive NMT program; CON: No intervention	6 weeks; 3 times per week; 60 min	Unilateral landing after a Standing long jump; Bilateral landing after a forward jump	5
Zech et al.; 2014; Germany	RCT	30 field hockey players; INT: 15, age 15.7 (3.9); CON: 15, age 14.1 (1.4); 0%	INT: Progressive NMT program; CON: No intervention	10 weeks; 2 times per week; 20 min	Star excursion balance test; BESS; Time-to-stabilization; Single-leg stance (center of pressure)	7
Root et al.; 2015; United States	RCT	89 students - members of school sport teams; INT1: 27, age 13 (2); CON1: 32, age 13 (1); CON2: 30, age 13 (2); 33%	INT1: ACL IPP; CON1: Static warm-up program; CON2: Dynamic warm-up program	1 session; 10–12 min	LESS; Countermovement jump; Standing long jump; Shuttle run (30 m down-and-back twice)	8

(continued)

Table 2. (continued)

Study; Publication Date; Country	Design	Participants (n); Age (years)[a]; Sex (% Female)	Intervention	Duration of intervention; frequency; duration of session	FMS-related outcomes	PEDro score
Rössler et al.; 2016; Switzerland	Cluster-RCT	122 soccer players; INT: 56, age 10.0 (1.8); CON: 66, age 10.1 (1.6); 0%	INT: FIFA 11+ Kids; CON: Sham treatment	10 weeks; 2 times per week; 15 min	Single-leg stance (center of pressure); Y-balance test; Countermovement jump; Standing long jump; 20 m Sprint; Slalom dribbling test; Wall-volley test	7
Ayala et al.; 2017; Spain	RCT	41 soccer players; INT1: 10; CON1: 11; INT2: 10; CON2: 10; age INT1, INT2, CON1 and CON2 16.8 (0.7); 0%	INT1: FIFA 11+; CON1: No intervention; INT2: Harmoknee warm-up program; CON2: No intervention	4 weeks; 3 times per week; 20 min	Y-balance test; Single-leg hop for distance; Triple-hop for distance; 10 m and 20 m Sprint	7
Ondra et al.; 2017; Czech Republic	RCT	21 basketball players; INT: 10, age 17.3 (1.3); CON: 11, age 16.5 (1.8); 0%	INT: Propioceptive and NMT program; CON: No intervention	20 weeks; 3 times per week; 20 min	Single-leg stance (center of pressure)	6
Akbari et al.; 2018 and 2019; Iran	RCT	24 soccer players; INT: 12; CON: 12; age INT and CON 16.79 (1.18); 0%	INT: FIFA 11+; CON: No intervention	8 weeks; 3 times per week; 20–25 min	Vertical jump; LESS	6
De Ste. Croix et al.; 2018; United Kingdom	Cluster-RCT	125 soccer players; INT: 71, age 13.1 (1.7); CON: 54, age 12.8 (1.6); 100%	INT: Progressive multicomponent robustness training program; CON: No intervention	16 weeks; 3 times per week (1 coach-led warm-up + 2 player-led sessions); 20 min	Submaximal hopping protocol (20 hops to test leg stiffness); Single-leg countermovement jump (vertical stop-jump task)	7
Gatterer et al.; 2018; Austria	RCT	16 soccer players; INT: 8; CON: 8; age INT and CON 10; 0%	INT: FIFA 11+; CON: No intervention	5 weeks; 2 times per week; 30 min	Standing long jump; Stability	6
Pomares-Noguera et al.; 2018; Spain	RCT	23 soccer players; INT: 13; CON: 10; age INT and CON 11.8 (0.3); 0%	INT: FIFA 11+ Kids; CON: No intervention	4 weeks; 2 times per week; 15–20 min	Y-balance test; 20 m sprint; Countermovement jump; Standing long jump; Slalom dribbling test; Wall-volley test	7
Taylor et al.; 2018; United States	Cluster-RCT	97 basketball and soccer players; INT: 48, age 15.4 (1.0); CON: 49, age 15.7 (1.6); 100%	INT: Warm-up-based ACL IPP; CON: No intervention	6 weeks; 2–3 times per week; 20–25 min	Countermovement jump; Single-leg hop test; Standing long jump; Single-leg hop (distance); Lateral jump; Triple-hop test; Single-leg lateral jump	7

(continued)

Table 2. (continued)

Study; Publication Date; Country	Design	Participants (n); Age (years)[a]; Sex (% Female)	Intervention	Duration of intervention; frequency; duration of session	FMS-related outcomes	PEDro score
Zarei et al.; 2018; Iran	Cluster-RCT	66 soccer players; INT: 34, age 15.03 (0.7); CON: 32, age 15.22 (0.6); 0%	INT: FIFA 11+; CON: No intervention	30 weeks; 2 times per week; 20-25 min	Dribbling sprint test; 9.1 m and 36.6 m sprint; Vertical jump	5
Zarei et al.; 2018; Iran	RCT	42 soccer players; INT: 19, age 11.93 (1.91); CON: 23, age 12.16 (1.13); 0%	INT: FIFA 11+ Kids; CON: No intervention	10 weeks; 3 times per week; 20 min	Slalom dribbling test; Standing long jump; Triple-hop for distance; Y-balance test; 20 yard and 40 yard sprint	4
McKenzie et al.; 2019; New Zealand	Cluster-RCT	81 netball players; INT: 45, age 13.33 (0.34); CON: 36, age 13.25 (0.50); 100%	INT: Netball Smart Dynamic Warm-up (NDW); CON: No intervention	7 weeks; 3 times per week; 15–20 min	Y-balance test; 20 m sprint; Standing long jump; Countermovement jump; Time-to-stabilization	5
Pardos-Mainier et al.; 2019; Spain	RCT	32 soccer players; INT: 15, age 12.5 (0.4); CON: 17, age 13.1 (0.3); 100%	INT: FIFA 11+; CON: No intervention	10 weeks; 2 times per week; 15–20 min	Standing long jump; Single-leg hop test; Countermovement jump; Single-leg countermovement jump; Y-balance test	5
Parsons et al.; 2019; Canada	Cluster-RCT	43 soccer players; INT: 25, age 11.1 (Range 10.1-11.7); CON: 18, age 10.8 (Range 9.5-11.7); 100%	INT: FIFA 11+; CON: No intervention	Indoor soccer season (5 month); 1–3 times per week; 20 min	LESS; Y-balance test; Countermovement jump	7
Trajkovic & Bogataj; 2020; Serbia	RCT	66 volleyball players; INT: 32, age 11.12 (0.68); CON: 34, age 10.96 (0.75); 100%	INT: Progressive NMT program; CON: No intervention	10 weeks; 2 times per week; 30 min	Lateral jumps; Single-leg hop test; 10 m sprint; Countermovement jump; Medicine ball Throw	6
Forrest et al.; 2020; Australia	Cluster-RCT	65 cricket players; INT: 32, age 15.8 (1.0); CON: 33, age 15.4 (1.2); 0%	INT: Progressive cricket IPP; CON: No intervention	8 weeks; 2 times per week; 15 min	SEBT	7
Font-Lladó et al.; 2020; Spain	RCT	190 children; INT 97, age 7.47 (0.27); CON 93, age 7.39 (0.38); 52.63%	INT: Pedagogical Integrative NTM; CON: No Intervention	12 weeks; 2 times per week; 20 min	CAMSA (FMS score)	6
Teixeira et al.; 2021; Brazil	RCT	24 soccer players; INT: 12, age 10.0 (0.6); CON: 12, age 9.75 (0.75); 0%	INT: FIFA 11+ Kids; CON: No intervention	8 weeks; 3 times per week; 30 min	Countermovement jump	5

[a]Data are mean (SD) except where otherwise stated. IPP = injury prevention program; NMT = neuromuscular training; RCT = randomized controlled trial; INT = intervention group; CON = control group; NA = not available; PEP = prevent injuries enhance performance; ACL = anterior cruciate ligament; LESS = Landing Error Scoring System; BESS = Balance Error Scoring System; CAMSA = Canadian Agility and Movement Competence Assessment.

Effects of the Interventions

Twenty-one articles studied the effects of MIPP compared to control groups by using frequentist statistics and determining statistical significance based on P-values. Eight articles reported positive-statistically-significant effects of MIPP in all their outcomes.[37,38,42,45,47,49] Positive effects were reported for vertical jump performance,[37,38,42,47] running performance,[42,47] postural stability,[36,45] landing technique,[37,38] dribbling in soccer,[47] the motor quotient in the Körperkoordinationstest für Kinder (movement competence assessment tool),[49] and the FMS score in the Canadian Agility and Movement Skill Assessment (CAMSA).[53]

Nine articles reported a combination of positive-statistically-significant and non-statistically-significant effects of MIPP in their outcomes.[33,35,39,40,43,44,46,52] Significant positive effects were reported for vertical jump performance,[40,44] running performance,[51] knee flexion angle,[43] between knee distance,[43] maximal knee abduction torque,[43] postural stability,[35,40,46] hip flexion angle,[39] landing technique,[33] dynamic balance,[44,51] triple hop test,[52] impulse peak force,[54] and maximum impulse force.[54] Non-statistically-significant effects were reported for vertical jump performance,[33,40,43,46] horizontal jump performance,[33,44] running performance,[33,44] maximal knee internal rotation angle,[43] postural stability,[35,40,46] hip adduction,[39] knee flexion,[39] knee abduction,[39] dynamic balance,[35] center of pressure,[35] dribbling in soccer,[51] single-leg hop test,[46] jump duration time,[54] maximum power output,[54] and force development rate.[54]

Four articles reported non-statistically-significant effects of MIPP in all their outcomes.[18,31,48,50] Non-statistically-significant effects were reported for vertical jump performance,[48,50] running performance,[48,50] knee valgus angle,[48] dribbling in soccer,[48] hip flexion,[18] hip adduction,[18] hip internal rotation,[18] knee flexion,[18] knee abduction,[18] knee internal rotation,[18] landing technique,[31] and dynamic balance.[31]

Six articles used magnitude-based inferences to study the effects of the MIPP compared to control groups.[29,30,32,34,41,52] Magnitude-based inferences are based on uncertainty in the true value of a statistic, which is expressed as confidence limits. The confidence limits are interpreted based on a three-level scale of magnitudes: beneficial, trivial, and harmful; then, an associated likelihood is stated.[55] Beneficial effects and their likelihoods were reported for vertical jump performance,[29,32,34,51] running performance,[29,51] horizontal jump performance,[32,34] dynamic balance,[29,32,34] reactive strength index of vertical jump after a drop jump,[34] dribbling in soccer,[34] leg stiffness,[29,30] knee valgus,[30] and sensory and stability indices.[41] Trivial effects were reported for single-leg stance,[34] running performance,[34] and dribbling in soccer [32]; conversely, one article reported possible harmful effects for dribbling sprint test in soccer.[51]

Meta-Analyses

We conducted six meta-analyses to estimate pooled effect sizes based on the outcomes that were reported in at least five studies. Meta-analyses for locomotor skills were completed on 738 participants for vertical jump performance (Figure 2), 363 participants for horizontal jump performance (Figure 3), 483 participants for running speed (Figure 4), and 349 participants

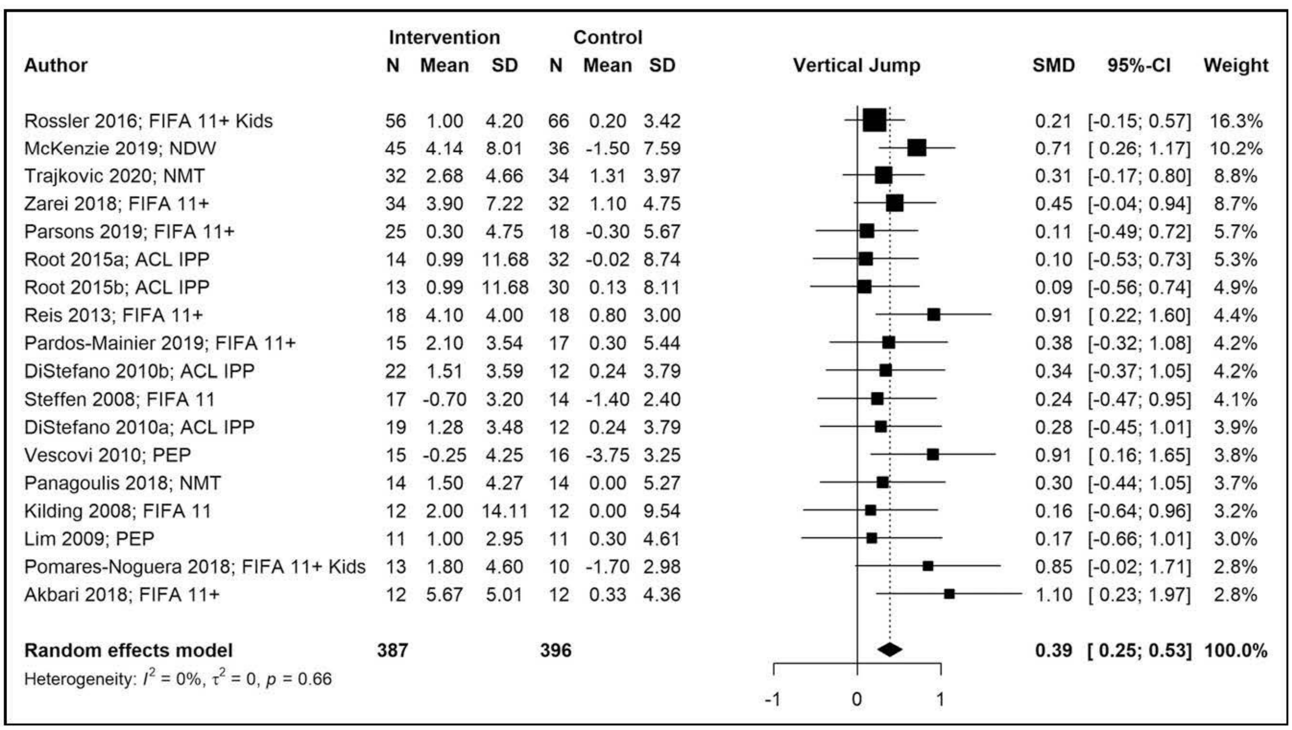

Figure 2. Forest plot and pooled effect size for vertical jump performance. SMD = Standardized mean difference; ACL = Anterior Cruciate Ligament; IPP = injury prevention program; NMT = neuromuscular training; PEP = prevent injuries enhance performance; NWD = Netball Dynamic Warm-up.

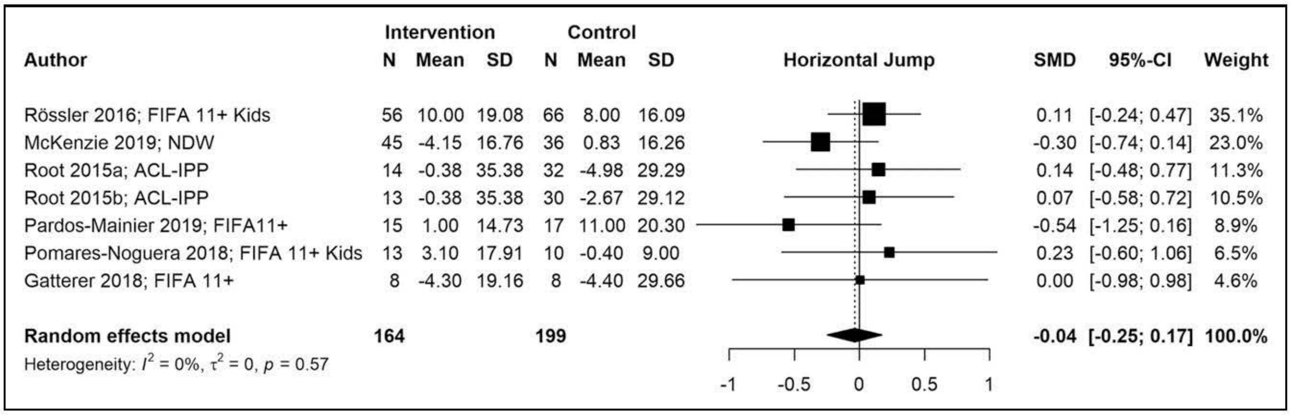

Figure 3. Forest plot and pooled effect size for horizontal jump performance. SMD = Standardized mean difference; ACL = Anterior Cruciate Ligament; IPP = injury prevention program; NWD = Netball Dynamic Warm-up.

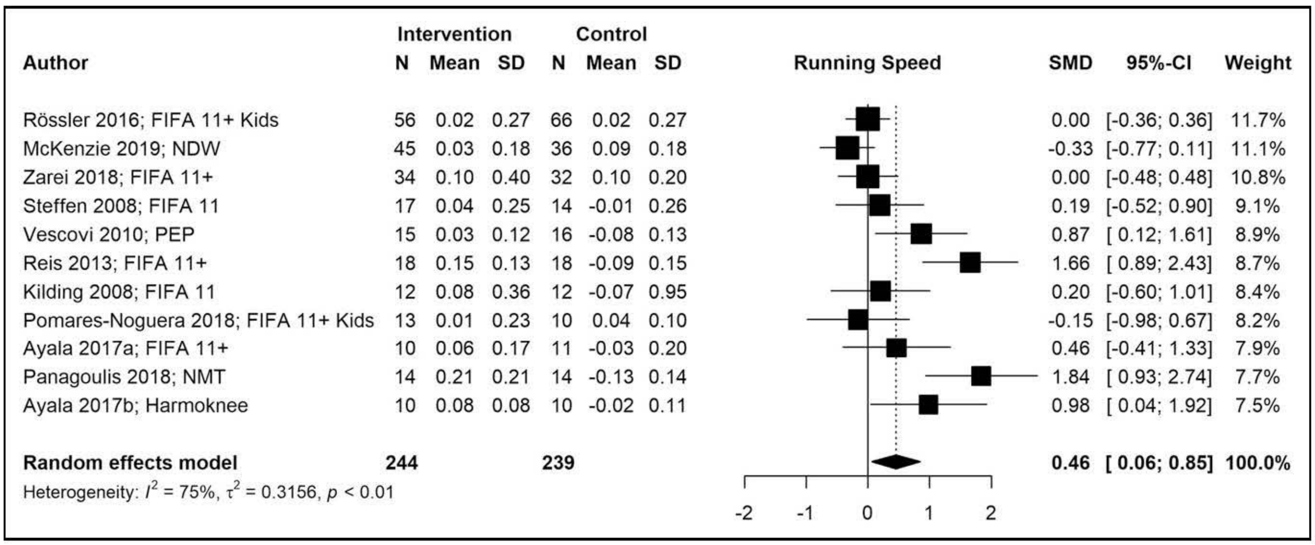

Figure 4. Forest plot and pooled effect size for running speed. SMD = Standardized mean difference; NMT = neuromuscular training; PEP = prevent injuries enhance performance; NWD = Netball Dynamic Warm-up.

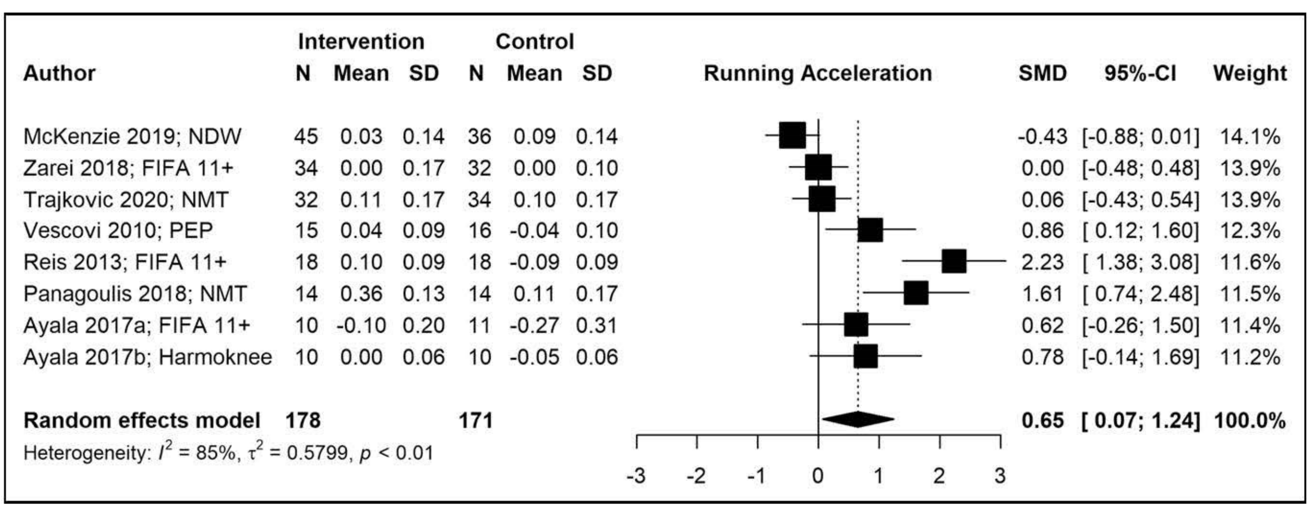

Figure 5. Forest plot and pooled effect size for running acceleration. SMD = Standardized mean difference; NMT = neuromuscular training; PEP = prevent injuries enhance performance; NWD = Netball Dynamic Warm-up.

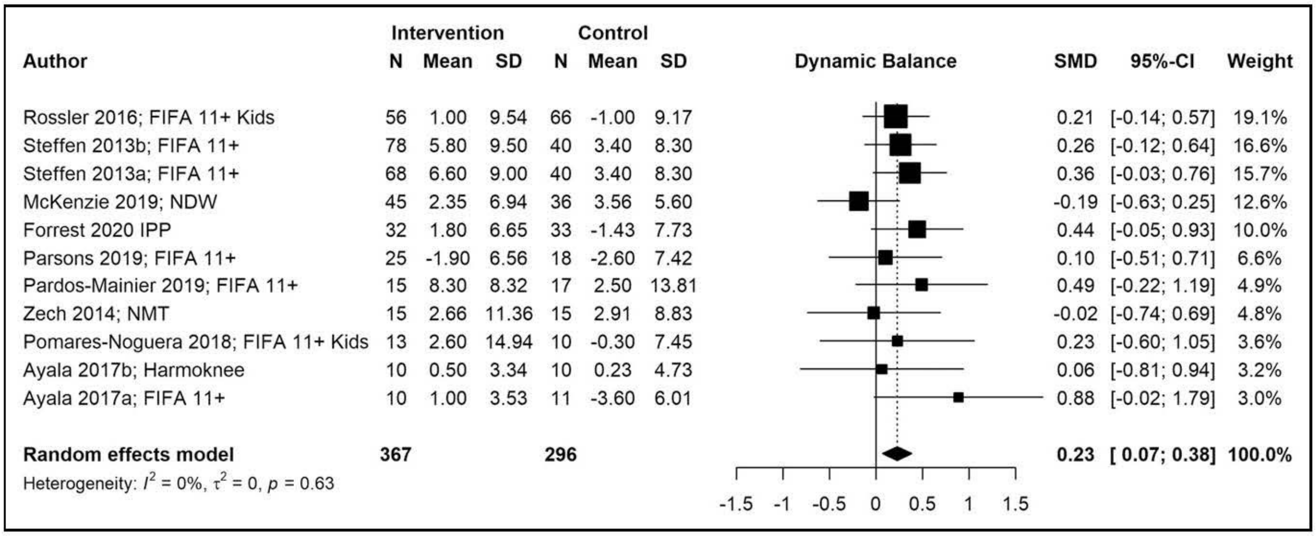

Figure 6. Forest plot and pooled effect size for dynamic balance. SMD = standardized mean difference; NMT = neuromuscular training; NWD = netball dynamic warm-up.

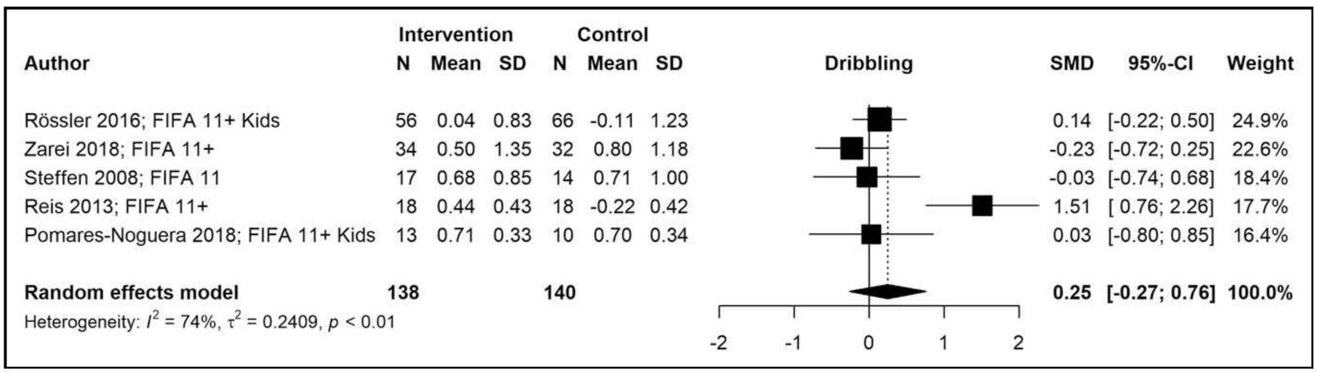

Figure 7. Forest plot and pooled effect size for dribbling. SMD = Standardized mean difference.

for running acceleration (Figure 5). Running performance was divided into speed when measured between 10 m and 40 m, and acceleration when measured between 0 m and 10 m. Meta-analyses for balance skills and object manipulation skills were completed on 663 participants for dynamic balance (Figure 6), and 278 participants for dribbling in soccer (Figure 7).

Locomotor skills. We observed significant positive pooled effect sizes for vertical jump (g = .39; 95% CI: [.25, .53]; $p <$ .001), running speed (g = .46; 95% CI: [.06, .85]; p = .024), and running acceleration (g = .65; 95% CI: [.07, 1.24]; p = .028). Conversely, horizontal jump presented a non-significant negative pooled effect size (g = −.04; 95% CI: [−.25, .17]; p = .724). Vertical jump and horizontal jump presented low heterogeneity (I^2 = 0%), indicating that included effect sizes were similar. Running speed (I^2 = 75%) and running acceleration (I^2 = 84%) presented high heterogeneity, indicating variability among effect sizes of individual studies.

Balance skills. We observed a significant positive pooled effect size for dynamic balance (g = .23; 95% CI: [.07, .38]; p = .004). The low heterogeneity of the meta-analysis (I^2 = .0%) indicated that included effect sizes were similar.

Object control skills. We observed a non-significant positive pooled effect size for dribbling (g = .25; 95% CI: [−.27, .76]; p = .345). The high heterogeneity of the meta-analysis (I^2 = 74%) indicated variability among effect sizes of individual studies.

Risk of Publication Bias Assessment

Funnel plots and Egger's regression tests did not suggest a risk of publication bias in vertical jump (p = .377), horizontal jump (p = .903), dynamic balance (p = .655), and dribbling (p = .560) measures. Significant Egger's test confirmed funnel plot asymmetry in running speed (p = .023) and running acceleration (p = .006) meta-analyses.

Discussion

The objective of this study was to synthesize the evidence on the effects of MIPP on biomechanical outcomes and neuromuscular performance measured on children and adolescents while performing FMS. Included studies reported that MIPP had a combination of positive-statistically-significant effects and non-statistically-significant effects on the biomechanics and neuromuscular performance of the three categories of FMS: locomotion, balance, and object manipulation skills. At least one positive/beneficial effect was reported in 23 of the 27 included articles. Meta-analyses showed significant positive pooled effects sizes for vertical jump performance, running speed, running acceleration, and dynamic balance, non-significant positive pooled effect size for dribbling, and non-significant negative pooled effect size for horizontal jump performance. Considering the relevance of FMS to promote physical activity in multiple contexts, the implementation of MIPP in physical literacy interventions, physical education classes, and organized physical activity is supported by the positive effects of MIPP in specific FMS and their reported effectiveness in reducing injury rates.[11]

Multicomponent Injury Prevention Programs

The characteristics of the MIPP studied on this review are similar to the characteristics of the interventions studied in other systematic reviews and meta-analyses focused on the same population.[11,15,20,56] All MIPP in the included articles, combined at least three components from which strength, plyometrics, and balance components were the most used. Most of the included articles used MIPP 2-3 times per week during 6–10 weeks with 11–20-minute sessions. Twenty-five of the 27 articles used MIPP as a warm-up, which agrees with Lim et al. (2009) and Root et al. (2015) who suggested that MIPP are suitable warm-ups as they can induce acute and beneficial adaptations before an intense session where injuries can occur.[43,57]

Twenty-six of the 27 interventions were implemented in sports-related settings suggesting a potential underuse of MIPP in other contexts. Considering that participating in physical activity increases the risk of injury,[6,19] MIPP should be implemented in contexts such as physical literacy interventions, physical education classes, and organized physical activity. The potential underuse of MIPP in multiple contexts is unfortunate because meta-analytical data indicates that MIPP can result in an injury reduction of around 46% in sports-related settings.[11] The preventive effects of MIPP are associated to the modification of multiple risk factors of injury, such as postural control, strength, or flexibility deficits.[35,58] Although the primary objective of MIPP is to affect modifiable risk factors of injury, other reviews[15,20,56] and our meta-analyses reported improvements in neuromuscular performance and biomechanics in children and adolescents.

Effects of Multicomponent Injury Prevention Programs on Fundamental Movement Skills

The effects of MIPP on strength, power, agility, flexibility, and balance may act synergically to mitigate biomechanical risk factors for injury and improve neuromuscular performance in FMS.[7,59] Neuromuscular adaptations from MIPP result in motor unit coordination, firing, and recruitment, which are essential factors for the quality of the movement.[15,60,61] These neuromuscular adaptations along with the benefits of strength and plyometric training lead to locomotor skills improvements.[15,60,62] Plyometric exercises included in MIPP may induce adaptations in muscles' contractile elements and enhanced efficiency of the stretch-shorten-cycle function, which benefits unilateral and bilateral jumping performance.[37] The significant positive pooled effect size ($g = .39$) with narrow CI for vertical jump performance reflect these neuromuscular adaptations. Similarly, improved running performance ($g = .46$ for running speed and $g = .65$ for running acceleration) may be the product of enhanced neuromuscular activation (eg, firing frequency of motor units), improved ground contact time, and increased musculotendon unit stiffness.[63] Leg stiffness improvements contribute to a change in the activation of the musculotendon unit leading to increased pre-activation before ground contact (ie, feed-forward control) and increased co-contraction after ground contact (ie, feedback control), thus promoting enhanced stability upon landing in unilateral and bilateral tasks.[30]

The effectiveness of MIPP on landing mechanics may be the result of core and hip exercises as well as the feedback provided to correct lower-extremity and trunk alignment.[38] Hip abduction strength contributed to improved control of frontal-plane knee and hip motions during unilateral and bilateral landing tasks.[30,32] Meta-analytical data indicate that MIPP have the potential for successful modification in high-risk lower limb landing mechanics that lead to decreased lower limb injury rates, indicating that biomechanical adaptations are exercise-dependent.[20,39] For instance, Brown et al. (2014) reported that landing with increased knee flexion seems dependent on the training modality and the feedback associated with each training component.[39]

Balance exercises included in MIPP may induce task-specific neurological adaptations, suppress muscle stretching reflex excitability during postural tasks, and enhance co-contraction between agonist and antagonist muscles.[52,64] Enhanced control over center of gravity shifts and automatic postural response patterns are the likely mechanisms that account for the positive pooled effect size ($g = .23$) with narrow CI observed in the dynamic balance meta-analysis and balance performance in general.[45,65,66] Although balance was a small component of MIPP, individual studies and our meta-analysis reported positive effects suggesting that intense balance training programs may not be necessary to observe improvements in balance.[40]

Individual studies and our meta-analyses suggest that MIPP have the potential to induce positive effects on specific FMS; however, the success of MIPP is not universal and is influenced by various factors. Participant compliance, implementation fidelity, and adherence issues and the characteristics of the interventions can affect the effectiveness of MIPP.[18,48,50] Participants with the greatest compliance seem to experience greatest effects on biomechanical outcomes, neuromuscular performance, and injury rate reduction.[57,67] Parsons et al. (2019) indicated that only the participants who were most adherent to the intervention improved in dynamic balance performance.[31] Similarly, Steffen et al., (2013) reported a dose-response relationship between the number of sessions/exercises and performance.[67] Several factors can affect compliance; for instance, Kilding et al. (2008) stated that the intervention was repetitive and caused boredom in the participants, which may affect their willingness to actively participate in it.[42] Moreover, Vescovi and VanHeest (2010) suggested that stakeholders might be unwilling to include additional exercises to reduce injury risk because it may take too much time from the training/practice session, which directly affects implementation fidelity.[50]

Lack of participant compliance and implementation fidelity are well recognized problems in MIPP, but the literature provides some remedies. Compliance can be enhanced by including group activities and implementing sessions that require little time commitment.[43] Progressive exercises can also enhance participants' enjoyment, and an early intervention may help children and adolescent to get used to the routine and protocols of MIPP, resulting in better long-term compliance.[40,57] Padua et al. (2014) suggested that achieving participant compliance, long-term adoption, implementation fidelity, and sustainability of MIPP require the development of administrative support within the organizations.[68] Stakeholders must support the use of MIPP to promote widespread dissemination.[40] Demonstrating an injury rate reduction along with acute improvements in biomechanics and neuromuscular performance in FMS may provide instant gratification to stakeholders that may help enhance compliance.[57]

MIPP characteristics are also addressed by authors to explain their non-positive results. Some MIPP with varying levels of training volume, intensity, progression, and content might have been insufficient to improve performance in specific studies.[18,31,48,50] Taylor et al. (2018) suggested that MIPP may not provide the appropriate stimulus to modify lower extremity biomechanics within a 6-week period with two sessions per week.[18] Additionally, Taylor also stated that MIPP often emphasize on double-leg and sagittal plane movements hindering biomechanical adaptations during single-legged and/or frontal plane movements.[18] Gatterer et al. (2018), McKenzie et al. (2019), and Pardos-Mainier et al. (2019) reported that MIPP often do not include many horizontal jumps, which may explain the non-significant negative pooled effect ($g = -.04$) in horizontal jump performance.[41,44,46] The focus and feedback strategy used on MIPP can also affect the effectiveness of the interventions.[7] Vescovi and VanHeest (2010) suggested that MIPP that heavily focus on reducing landing forces may fail to improve jump performance.[50] Conversely, Steffen et al. (2008) reported that participants might have developed leg power, but a poor technique may explain the poor jumping performance, suggesting that more feedback was needed.[48]

Dribbling was the only object control skill with the sufficient data to conduct a meta-analysis. Although dribbling was particular to soccer, it provided insights into the effects of MIPP in context-specific tasks. The pooled effect size of dribbling was positive ($g = .25$) but non-significant; specifically, three studies reported positive effects,[32,34,47] and two studies reported negative effects.[48,52] Since dribbling was assessed in a soccer context, the ambiguous results may be due to highly specialized and skilled participants with little room for improvement. Despite these results, developing MIPP that include object control skills is relevant because improved neuromuscular control during these skills may enable participants to process environmental stimuli better and faster, favoring the attentional capacity and movement competence.[15]

Limitations

This systematic review with meta-analysis has some limitations. Although we defined a priori inclusion and exclusion criteria, we conducted the narrative synthesis and meta-analyses based on substantially different studies regarding the participants, content, characteristics, and outcomes of the interventions. For example, assessments in selected studies were different, and their comparability was affected, which may lead to discrepancies in the results. We investigated outcomes related to all FMS categories; however, included studies did not report on some common FMS (eg, leaping and galloping). We extracted and reported a series of biomechanical and neuromuscular performance outcomes, but we could not conduct meta-analyses for any biomechanical outcome because we required at least five studies reporting the same outcome to achieve reasonable power for a random-effects model.[27] Running speed, acceleration, and dribbling meta-analyses should be cautiously interpreted due to their high heterogeneity values. Potential publication bias indicates that running speed and acceleration pooled effect sizes may be overestimated despite their significant positive results. Only the first author extracted the data, which increases the probability of human mistakes in the data extraction process; however, a second researcher did random data-checks as part of the quality control of the systematic review.

Conclusions

MIPP positively influenced specific biomechanical outcomes and neuromuscular performance measured on children and adolescents while performing FMS. Short MIPP that focus on progression and a variety of movement skills should be implemented at the beginning of a session as lengthy interventions can negatively affect participant compliance.[39,42]

Properly designed MIPP must consider training specificity, intensity, and volume to provide enough stimuli to lead to positive biomechanical and neuromuscular performance effects in FMS. Stakeholders' involvement needs to be prioritized to enhance implementation fidelity. Athletes benefited from MIPP in sports-related settings, so it is plausible that less specialized individuals will also benefit from MIPP; moreover, implementing MIPP in physical literacy interventions, physical education classes, and organized physical activity may help promote safe physical activity as MIPP can reduce injury risk and positively affected neuromuscular performance.

So What?

What is Already Known on This Topic?

Multicomponent injury prevention programs (MIPP) are used to reduce musculoskeletal injury risk and enhance health- and -skill-related fitness. Fundamental movement skills (FMS) are commonly used in MIPP and play a significant role in physical literacy, physical education, and organized physical activity.

What Does This Article Add?

MIPP positively affected specific biomechanical outcomes and neuromuscular performance measured in children and adolescents while performing FMS. Implementing MIPP in physical literacy, physical education, and organized physical activity may help promote safe physical activity as FMS are used and assessed in the physical activity and injury prevention fields.

What are the Implications for Health Promotion Practitioners or Research?

The potential functional adaptations and the preventive capacity of MIPP are relevant arguments to convince stakeholders to implement MIPP outside sport-related contexts. Lack of compliance reduces the potential effects of MIPP. Future research should investigate the implementation of MIPP outside sport-related contexts.

Author Contributions

JJ-G conceptualized and designed the work, collected, extracted, and analyzed the data, and drafted the manuscript. MM substantially contributed to the data collection/extraction process and revised the manuscript critically for relevant content. RD made a substantial contribution to the concept and design of the work and revised the manuscript critically for relevant content.

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Supplemental Material

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Transition to Chapter Three

Chapter two contributed to the theoretical foundation for the development and implementation of a neuromuscular warm-up based on movement skills within a framework that combined the physical literacy model and multicomponent injury prevention programs (MIPP).

Chapter three aimed to test the validity of the Child Focused Injury Risk Screening Tool (ChildFIRST). We developed the ChildFIRST and established its preliminary validity and reliability evidence at the Athletic Therapy Research Laboratory at Concordia University. The validity (https://doi.org/10.1080/1091367X.2020.1793344) and reliability (https://doi.org/10.1080/1091367X.2020.1781129) studies are not part of this dissertation and were published in *Measurement in Physical Education and Exercise Science.*

The manuscript presented in chapter three is under review in *Measurement in Physical Education and Exercise Science* and describes the testing of the concurrent and convergent validity of the ChildFIRST.

Chapter Three: Manuscript Two

Concurrent and Convergent Validity of The Child Focused Injury Risk Screening Tool (ChildFIRST) for 8-12-Year-Old Children

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Under review in: *Measurement in Physical Education and Exercise Science.*

Note: The manuscript in chapter three has the referencing style required by the *Measurement in Physical Education and Exercise Science*. We kept this format to maintain the integrity of the manuscript. No content has been modified.

3.1 Abstract

The Child Focused Injury Risk Screening Tool (ChildFIRST) aims to measure movement competence and lower-limb-injury risk in 8-12-year-old children. Although the ChildFIRST has face and content validity evidence, stronger validity evidence is warranted. We tested the concurrent validity of the ChildFIRST using motion analysis, and the convergent validity of the ChildFIRST using the modified Star Excursion Balance Test (mSEBT) and the Test of Gross Motor Development 3 (TGMD-3). We computed correlation coefficients (0.05 alpha level). We evaluated 17 participants. We observed positive correlation values between 18 ChildFIRST evaluation criteria and peak joint angles in the frontal and sagittal planes. One movement skill (i.e., leaping) presented a negative correlation value. We observed positive correlation values between the ChildFIRST and TGMD-3 and between the ChildFIRST and the mSEBT. Nine out of ten movement skills in the ChildFIRST are valid to assess movement competence and identify risk factors associated to lower-limb musculoskeletal injuries.

Keywords. Movement competence, validity, screening tool, assessment tool, musculoskeletal

3.2 Introduction

Empirical and theoretical evidence supports an interaction between movement competence, perceived movement competence, physical activity (PA), health-related fitness, and weight status (Barnett et al., 2022; Robinson et al., 2015; Stodden et al., 2008; van Veen et al., 2020). Movement competence describes goal-oriented proficiency in any movement-based activity (Bardid et al., 2019; Robinson et al., 2015). In the literature, several terms are used interchangeably with movement competence; for instance, motor competence, fundamental movement skills proficiency, and physical competence (Bardid et al., 2019). Movement competence is a key construct for different motor development models (Goodway et al., 2019), and it is also a relevant construct of the physical factor of the physical literacy model (Whitehead, 2001). Motor development is a dynamic non-linear process that refers to the ability of individuals to develop, improve, and use their physical skills (Goodway et al., 2019). The physical literacy model, which was originally proposed by Whitehead in 2001 and evolved over the years, aims to promote lifelong PA by targeting affective (e.g., confidence, motivation), cognitive (e.g., knowledge, understanding), physical (e.g., movement competence, physical fitness), and behavioral factors (e.g., daily PA) (Whitehead, 2001).

Childhood is considered as an opportunity to improve movement competence and engage with PA to enhance health trajectories in the adulthood (Bardid et al., 2019; Burton & Miller, 1998). Children and adolescents with higher movement competence are likely to participate in PA and sports, which is hypothesised to promote further development of movement competence (Barnett et al., 2022; Stodden et al., 2008). Theoretical models and empirical evidence suggest that movement competence also has bidirectional relationships with perceived movement competence, health related fitness, and weight status (Barnett et al., 2022; Robinson et al., 2015).

Thus, assessing movement competence is relevant to public health due to its relationships with increased levels of PA and other health determinants (Hulteen et al., 2020).

Movement competence assessment tools aim to identify developmental delays by assessing the degree of proficiency in performing a wide array of movement skills (Bardid et al., 2019; Hulteen et al., 2020; Palmer et al., 2021). Movement competence assessment tools are either process-based, product-based, or a combination of both (Hulteen et al., 2020; Logan et al., 2017; Palmer et al., 2021). Process-based assessment tools assess the quality of the movement (e.g., posture, joint alignment) by relying on the presence of specific evaluation criteria (Logan et al., 2017; Palmer et al., 2021). Product-based assessment tools solely focus on quantitative outcomes of the movement (e.g., jump height) (Logan et al., 2017; Palmer et al., 2021). Although many movement competence assessment tools exist, a "gold standard" tool, which is consistently used across age groups, cultures, and geographic regions, does not exist (Hulteen et al., 2020).

Researchers and practitioners use movement skills to operationalize movement competence (Barnett et al., 2020; Hulteen et al., 2018; Logan et al., 2017). Fundamental movement skills are the foundation for more complex/specialized movement skills and are indispensable to accomplish everyday activities and engage in PA and sports (Goodway et al., 2019). Fundamental movement skills are classified as object control skills (e.g., kicking, throwing), locomotor skills (e.g., running, jumping), and balance skills (e.g., balance, postural control) (Burton & Miller, 1998; Goodway et al., 2019; Palmer et al., 2021). Assessment of fundamental movement skills can provide a fair overview of movement competence. Including the assessment of basic human movements can complement and help to better understand individuals' movement behavior (Tompsett et al., 2014). Basic human movements are essential movement patterns (e.g., pull, push, squat) that allow individuals to interact with the environment in different contexts and directly influence children's and adolescent's movement competence (Tompsett et al., 2014).

Movement competence assessment tools and interventions typically focus on addressing developmental delays and taking advantage of the health benefits of movement competence in typically developing children (Barnett et al., 2020, 2022; Palmer et al., 2021). Movement-based strategies are used to promote PA; however, an increased risk of musculoskeletal injuries is inherent to any movement-based activities and PA (Armstrong & Mechelen, 2017; Longmuir et al., 2014; Miller et al., 2018). Musculoskeletal injuries are not commonly addressed by current assessment tools and may be undermeasured outside of sports contexts (Jimenez-Garcia et al., 2020; Miller et al., 2018). Epidemiological data and etiological models suggest that jumping, landing, and cutting tasks are associated with increased risk of noncontact musculoskeletal injuries during middle and late childhood (Emery, 2010; Lykissas et al., 2013; Meeuwisse et al., 2007; Rössler et al., 2016). Although the PA-related risk of musculoskeletal injuries during childhood is low when compared to adolescents and adults, these injuries may lead to health-related problems and represent a significant socioeconomical burden (Bloemers et al., 2012; Cai et al., 2018; Räisänen et al., 2018). Moreover, individuals who do not address movement competence deficiencies early in life may be less motivated and lack the skills to engage in lifelong PA, and may also have a higher risk of injury (Bahr & Holme, 2003; Faigenbaum et al., 2020; Jimenez-Garcia et al., 2022).

In PA and sports settings, researchers and practitioners strive to reduce musculoskeletal injury rates by using injury prevention strategies (Emery, 2010; Jimenez-Garcia et al., 2022). Injury prevention strategies include musculoskeletal injury screening, which involves the systematic observation of an individual's movement patterns, range of motion, joint alignment, strength, posture, and balance/stability (Read et al., 2019). Musculoskeletal injury screening tools synthesize biomechanical, neuromuscular, and movement competence observations to objective metrics, which can help to guide targeted strategies in different contexts (Burton & Miller, 1998; Myer et al., 2011). Musculoskeletal injury screening complements other sources of information (e.g., type of sport, setting, sport specialization, physiological and anatomical factors) to understand individual's risk of musculoskeletal injuries (Emery, 2010; Räisänen et al., 2018).

Due to the lack of a "gold standard" for movement competence assessment and the absence of a field-based movement competence assessment tool that incorporates an injury screening approach, a research group developed the Child Focused Injury Risk Screening Tool (ChildFIRST) (Jimenez-Garcia et al., 2020). The ChildFIRST is a process-based tool that measures two constructs, movement competence and risk of lower limb musculoskeletal injury, using ten movement skills, each with four evaluation criteria (Jimenez-Garcia et al., 2020; Miller et al., 2020). The movement competence construct focuses on the execution of movement skills from a motor development perspective (Goodway et al., 2019; Jimenez-Garcia et al., 2020). The risk of musculoskeletal injury construct focuses on lower limb motion in both the sagittal and frontal planes (Jimenez-Garcia et al., 2020).

The ChildFIRST was developed using a modified Delphi method, which provided face and content validity evidence based on expert opinion (Jimenez-Garcia et al., 2020). However, face and content validity are the least robust forms of validity, and stronger validity evidence is warranted for the ChildFIRST. We aimed to test the concurrent and convergent validity of the ChildFIRST. Concurrent validity refers to the extent to which scores on a particular tool relate to a “gold standard” (Kline, 2008). Convergent validity indicates the similarity of results between related tools when a "gold standard" is not available (Kline, 2008). To test the concurrent validity, we compared the ChildFIRST results against three-dimensional (3D) models. As the ChildFIRST focuses on lower limb musculoskeletal injury risk, we only tested the concurrent validity of the evaluation criteria used to assess lower limb alignment in the frontal and sagittal planes, which represented 18 out of its 40 evaluation criteria. The other 22 evaluation criteria relate more to movement competence (e.g., looking forward while running, or alternating arms and legs while running) and its validation using 3D motion analysis of these criteria was not feasible. To test the convergent validity, we compared specific movement skills in the ChildFIRST against the Test of Gross Motor Development 3 (TGMD-3) and the modified Star Excursion Balance Test (mSEBT) (Coughlan et al., 2012; Webster & Ulrich, 2017). We hypothesized that the ChildFIRST has concurrent and convergent validity when compared to 3D motion analysis, the TGMD-3, and the mSEBT.

3.3 Methods

3.3.1 Study Design and Setting

We conducted a validation/cross-sectional study. We used the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement to report this study (von Elm et al., 2007). The testing sessions were conducted in a functional assessment laboratory in a university research center between the years 2021 and 2022. This study had institutional ethics approval (certificate number 30004928).

3.3.2 Participants

We recruited 17 apparently healthy children using a convenience sampling method through posters and online advertisement. We calculated the sample size by conducting an *a priori* power analysis based on a correlation coefficient of 0.7 with an alpha equal to 0.05 and a beta equal to 0.1. *Inclusion criteria.* Participants were injury-free and aged between 8 and 12 years. *Exclusion criteria.* Participants who: (1) lived with overweight or obesity, which was determined using the body mass index (BMI); (2) reported injuries for six weeks before the testing session; (3) reported any recurrent injury that kept them from training for more than 30 days in the past year; (4) were in post-operative rehabilitation; (5) lived with a cognitive impairment reported by parents; (6) are not within the defined age range.

3.3.3 Instruments

Motion Capture System

We used a Vicon motion capture system (Vicon Motion Systems INC, Oxford, UK) with eight infrared cameras (Vicon Near-IR camera system [MX T20]) to record the participants using a sampling frequency of 100 Hz while performing the ChildFIRST. We created 3D models for each movement skill. 3D motion capturing systems are considered as the “Gold Standard” for assessing kinematics during functional performance tests due to its precision and reliability (McLean, Walker, Ford, et al., 2005).

We also recorded the participants during the testing session using a standard video camera (Samsung, Seoul, South Korea) positioned in the frontal plane with a sampling rate of 50 Hz. We used the videos to evaluate the participants using the ChildFIRST and the TGMD-3.

The Child Focused Injury Risk Screening Tool (ChildFIRST)

The ChildFIRST is a field-based assessment tool that aims to test children in in-field settings (i.e., sport practices, physical education classes), requires minimal equipment, and consists of ten movement skills each with four evaluation criteria (Table 1) (Jimenez-Garcia et al., 2020). Each evaluation criterion on the ChildFIRST use dichotomous scoring: criterion not met (0) and criterion met (1), which are equally weighted and summed for each movement skill (up to 4 points) to determine a skill score and for all ten movement skills (up to 40 points) to determine a composite score. The ChildFIRST has face validity and content validity, which was tested through expert opinion using a modified Delphi process with an international expert panel (n =22) (Jimenez-Garcia et al., 2020). The ChildFIRST also has intra- and inter-rater reliability evidence, which was tested by 12 senior university students from movement-related programs (Miller et al., 2020).

[Insert Table 1]

Table 1. ChildFIRST Movement skills and Evaluation Criteria.(Jimenez-Garcia et al., 2020)

Movement Skill	Description	Evaluation Criteria
Bodyweight Squat	*Squatting involves flexing the knees and pushing the hips back to lower the center of gravity. The feet are shoulder-width apart and the hands are placed either crossed on the chest or extended out in front of the body. The movement should be smooth.*	Push the hips back and bend the knees until the thighs are approximately parallel with the ground Hips, knees, and ankles aligned Knees do not go too far in front of the toes Keep the heels down all the time
Single-Leg Hop	*Single-Leg Hop is performed by taking off from one foot and landing on the same foot. The movement should be smooth and performed equally on both sides.*	Hip, knee, and ankle aligned Take off from one foot, land on the same foot Knee and hip bend to land softly in a controlled fashion Swing arms to assist the movement
Running	*Running is faster than walking, but it is not sprinting. It will present the gait pattern (heel strike-midfoot-forefoot) and a flight phase. The ChildFIRST does not intend to measure how fast the child runs but the quality of the movement. The movement should be smooth.*	Upper-body straight and eyes focused on the direction travelled Swing bent arms in opposition to legs Knee drives upward and forward to lift the foot off the ground Knee and hip bend slightly to land softly
Vertical Jump	*Vertical jump is the action of propelling the body vertically into the air from the ground using both legs and landing with both feet. The movement should be smooth.*	Swing arms to assist the movement Knees and hips bend to land softly in a controlled fashion Land on both feet at the same time Hips, knees, and ankles aligned

Table 1. ChildFIRST Movement skills and Evaluation Criteria (Cont.).(Jimenez-Garcia et al., 2020; Miller et al., 2020)

Movement Skill	Description	Evaluation Criteria
Horizontal Jump	*Horizontal jump is the action of propelling the body horizontally into the air from the ground using both legs and landing with both feet. The movement should be smooth.*	Swing arms to assist the movement Knees and hips bend to land softly in a controlled fashion Land on both feet at the same time Hips, knees, and ankles aligned
Walking Lunge	*A lunge can refer to any position of the human body where one leg is positioned forward with knee bent and foot flat on the ground while the other leg is positioned behind. The movement should be smooth and performed equally on both sides.*	Hips, knees, and ankles aligned Upper-body straight and eyes focused on the direction travelled Front-knee does not go too far in front of the toes No twisting nor bending back
Two to One-foot Hop and Hold	*Two to One-foot Hop and Hold is a balance test in which the child starts with feet in a comfortable distance apart, hops forward, and lands on one foot. The child tries to recover and keep balance after landing.*	Knee and hip bend slightly to land softly in a controlled fashion Toes pointing forward Foot flat on the floor Hip, Knee, and ankle aligned
Single-Leg Sideways Hop and Hold	*Single-Leg Sideways Hop and Hold is a balance test in which the child tries to recover and keep balance after landing. The child starts by standing on one leg, jumps to the side of the free-leg, lands with the free-leg, and holds the position for three seconds.*	Knee and hip bend slightly to land softly in a controlled fashion Hip, Knee, and ankle aligned Foot flat on the floor Stand up straight within three seconds after landing

Table 1. ChildFIRST Movement skills and Evaluation Criteria (Cont.).(Jimenez-Garcia et al., 2020; Miller et al., 2020)

Movement Skill	Description	Evaluation Criteria
Leaping	*Leaping is the action of propelling the body forward and is performed by taking off on one foot and landing on the other foot. The movement should be smooth and performed equally on both sides.*	Take off from one foot, land on the opposite foot Knee and hip bend to land softly in a controlled fashion Hip, knee, and ankles aligned Swing bent arms in opposition to legs
90-Degree Jump and Hold	*90-Degree Jump and Hold is balance test in which the child stands on the right leg, hops, and turn 90 degrees to the right, and lands on the right foot. The child tries to recover and keep balance after landing. 90-Degree Jump and Hold is repeated using the left leg.*	Knee and hip bend slightly to land softly in a controlled fashion Hip, Knee, and ankle aligned Whole body turns together Toes pointing forward

The Test of Gross Motor Development 3 (TGMD-3)

The TGMD-3 is a process-based test of gross motor skills with a scoring system based on dichotomous evaluation criteria. The TGMD-3 has shown high test-retest reliability coefficients (ICC = 0.97) (Webster & Ulrich, 2017). Exploratory factor analysis and confirmatory factor analysis supported a one-factor model for gross motor skill competence for the TGMD-3 with 73.8% variance explained, showing acceptable construct validity (Webster & Ulrich, 2017). The psychometric properties of the translated versions of TGMD-3 are also supported by factor analysis (Maïano et al., 2022). We only evaluated running, horizontal jump, and single-leg hop from the TGMD-3 because they were the movement skills that matched with the ChildFIRST. We used the TGMD-3 due to its extensive validity and reliability evidence. The TGMD-3 is also a process-based test that uses a series of evaluation criteria and a dichotomous scoring system similar to the ChildFIRST.

The Modified Star Excursion Balance Test (mSEBT)

The mSEBT is used to evaluate dynamic balance and neuromuscular control of the lower extremities (Coughlan et al., 2012). This test measures an individual's ability to reach in three different directions (i.e., anterior, posteromedial, and posterolateral) while standing on one leg (Coughlan et al., 2012). The mSEBT is widely used to assess dynamic balance in healthy and injured populations (Calatayud et al., 2014). The mSEBT has moderate to good test-retest reliability coefficients (ICC = 0.51 to 0.93) estimated in primary school children (Calatayud et al., 2014). We normalized the reaching distances and composite score using the participant’s lower limb length. We used the mSEBT due to its practicability and its validity and reliability evidence.

3.3.4 Procedures

We obtained informed consent from the parents/guardians and verbal assent from the participants. Before the testing session, the parents/guardians and participants completed a baseline questionnaire to verify that participants met the inclusion criteria. We recorded the participants performing the ten movement skills in the ChildFIRST using the 3D motion capturing system and the standard video camera. We then used the mSEBT to evaluate the participants' dynamic balance.

Procedures for the 3D Motion Analysis

An investigator collected anthropometric data (i.e., height, weight, lower limb length, knee width, ankle width, shoulder offset, elbow width, and hand thickness) and placed 35 non-invasive reflective markers on specific anatomical landmarks on all participants according to the Plug-in-Gait full body marker set (Vicon Motion systems, 2010). We calibrated the system and set the volume origin (global coordinate system) using an active wand. We performed the static calibration and then recorded each movement skill individually. We captured the initial position, the performance of the movement skill, and the return to the initial position. We provided each participant with verbal standardized information (i.e., instructions and descriptions) on the performance of the movement skills. We allowed the participants to do up to three practice trials and rest as they feel necessary before test trials (McLean, Walker, & van den Bogert, 2005). The participants rested two minutes between test trials to perform each movement skill. A successful trial required the performance of the movement skill within the field of view of the standard video camera and the motion capture system (McLean, Walker, & van den Bogert, 2005). A trial was discarded if: (1) the participant fell, (2) the investigator determined that the movement is uncontrolled, (3) a reflective marker fell off, (4) the trial was interrupted, (5) the investigator made a mistake during the trial (Whatman et al., 2013).

Procedures for the Physical Test

All tests were administered by the same investigator, who received extensive training before data collection and was not blind to the details of the study. We used the videos recorded with the standard video camera to evaluate the participants using the ChildFIRST and the TGMD-3. When performing the mSEBT, the participants had four practice trials, which minimizes practice effects, then they rested two minutes before attempting the three test trials on each direction. A trial was invalid when the participant: (1) removed his hands from his hips, (2) placed the reach foot on the ground, (3) raised or moves the stance foot, (4) did not return to the starting position, (5) applied too much weight through the reach foot resulting in increased reach distances.

3.3.5 Data Processing

We used a 6 Hz zero-lag 4th order low-pass Butterworth filter to filter trajectory data. We used the Cardan sequence YXZ to calculate joint angles, which are equivalent to flexion/extension, abduction/adduction, axial rotation in the joint coordinate system as described by Grood and Suntay (1983) (Grood & Suntay, 1983). We manually conducted the gap-filling using the "Rigid Body" fill when we had three reference markers for the same structure (i.e., head, thorax, and pelvis) and the "Pattern" fill when we had a subjacent marker that follows a similar movement pattern (e.g., heel and ankle markers). We processed and exported all kinematic data using the Nexus 2.6.1 software (Vicon Motion Systems Ltd, UK) to provide peak joint angles for each movement skill.

3.3.6 Outcomes

We extracted peak flexion/extension and abduction/adduction angles for the knee and hip joint using the 3D motion capture system. We computed scores for each movement skill and the composite score of the ChildFIRST. We used the participants' videos of three movement skills (i.e., running, single-leg hop, horizontal jump) to evaluate the participants using the TGMD-3. We computed the mSEBT normalized composite score for each limb.

Correlations

We studied the correlations between: (1) peak knee and hip angles in the sagittal and frontal planes and the evaluation criteria (n=18) of the ChildFIRST; (2) the individual scores at the skill level of three movement skills from the TGMD-3 (i.e., running, single-leg hop, horizontal jump) and the corresponding movement skills in the ChildFIRST; (3) the mSEBT normalized composite scores and the dynamic balance skills of the ChildFIRST (i.e., two to one-foot hop and hold, single-leg sideways hop and hold, 90-degree jump and hold).

3.3.5 Statistical Analysis

We used Python 3.11 (Python Software Foundation, https://www.python.org/) for all statistical analyses. We performed exploratory data analysis to observe the distribution of the variables, treat potential missing values, and identify outliers. We evaluated all continuous data for normality and homoscedasticity. We computed point-biserial correlation coefficients to investigate the relationships between specific ChildFIRST evaluation criteria and joint peak angles from the frontal and sagittal planes in the lower limb. We computed correlation coefficients to test the concurrent validity of the ChildFIRST when compared to the TGMD-3 and the mSEBT. If any variable presented non-normal distribution, we used non-parametric tests (e.g., Spearman Rank Correlation). We used a 0.05 alpha level for all tests and reported point estimates, confidence intervals, and effect sizes.

3.4 Results

We did not identify any outliers, missing values and did not do any transformation to the data. We used non-parametric statistical tests because all continuous variables did not meet the normality assumption. Seventeen participants (82.35% male, age = 10.46 ± 1.46 y, height = 1.45 ± 0.13 m, weight = 36.86 ± 7.71 Kg) participated in the testing session. Demographic data and test results can be found on table 2.

Table 2. Participants' Demographic Characteristics and Physical Tests Results.

Variable	Mean (SD)
Age (y)	10.46 (1.33)
Height (m)	1.45 (0.13)
Weight (Kg)	36.86 (7.71)
BMI	17.13 (1.58)
BMI (percentile)	49.29 (19.21)
ChildFIRST Composite Score	29.12 (5.82)
mTGMD-3	17.29 (3.03)
Right Limb Length (cm)	75.53 (7.18)
Left Limb length (cm)	75.36 (7.16)
Norm. mSEBT Anterior - Right	89.96 (8.63)
Norm. mSEBT Posteromedial -Right	103.35 (9.85)
Norm. mSEBT Posterolateral -Right	102.54 (14.20)
Norm. mSEBT Composite - Right	98.62 (9.77)
Norm. mSEBT Anterior - Left	89.45 (8.78)
Norm. mSEBT Posteromedial -Left	103.01 (10.99)
Norm. mSEBT Posterolateral -Left	103.77 (13.92)
Norm. mSEBT Composite - Left	98.73 (10.45)

BMI = Body Mass Index; mTGMD-3 = Modified Test of Gross Motor Development (Running, Horizontal Jump, Single-Leg Hop); Norm. = Normalized; mSEBT = Modified Start Excursion Balance Test

3.4.1 Concurrent Validity

Sagittal plane kinematics were focused on the hip and knee peak flexion angles. Positive correlation coefficients between the evaluation criteria and peak knee flexion angle ranged between 0.45 and 0.77. Leaping was the only movement with a negative correlation coefficient for knee flexion angle (rpb = -054 [-0.81, -0.08] for the left knee and -0.29 [-0.68, 0.22] for the right knee). Positive correlation coefficients between the evaluation criteria and peak hip flexion angle ranged between 0.23 and 0.70. All correlations coefficients with confidence intervals and statistical significance can be found in table 3.

Table 3. Point Biserial Correlation Coefficients to Test the Concurrent Validity of the ChildFIRST Evaluation Criteria in the Sagittal Plane.

ChildFIRST Evaluation Criterion	Biomechanical Outcome	rpb [95%CI]
Bodyweight Squat - Push the hips back and bend the knees until the thighs are approximately parallel with the ground	Peak Left Knee Flexion	0.68 [0.29, 0.87]*
	Peak Right Knee Flexion	0.67 [0.28, 0.87]*
	Peak Left Hip Flexion	0.25 [-0.26, 0.65]
	Peak Right Hip Flexion	0.23 [-0.28, 0.64]
Vertical Jump - Knees and hips bend to land softly in a controlled fashion	Peak Left Knee Flexion	0.68 [0.3, 0.88]*
	Peak Right Knee Flexion	0.5 [0.02, 0.79]*
	Peak Left Hip Flexion	0.61 [0.19, 0.84]*
	Peak Right Hip Flexion	0.44 [-0.06, 0.76]
Horizontal Jump - Knees and hips bend to land softly in a controlled fashion	Peak Left Knee Flexion	0.74 [0.4, 0.9]*
	Peak Right Knee Flexion	0.62 [0.19, 0.85]*
	Peak Left Hip Flexion	0.46 [-0.03, 0.77]
	Peak Right Hip Flexion	0.43 [-0.06, 0.76]
Running - Knee and hip bend slightly to land softly	Peak Left Knee Flexion	0.76 [0.45, 0.91]*
	Peak Right Knee Flexion	0.47 [-0.02, 0.77]
	Peak Left Hip Flexion	0.23 [-0.28, 0.64]
	Peak Right Hip Flexion	0.34 [-0.17, 0.71]
Leaping - Knee and hip bend to land softly in a controlled fashion	Peak Left Knee Flexion	-0.54 [-0.81, -0.08]*
	Peak Right Knee Flexion	-0.29 [-0.68, 0.22]
	Peak Left Hip Flexion	0.33 [-0.17, 0.7]
	Peak Right Hip Flexion	0.31 [-0.2, 0.69]

Single-Leg Hop+ - Knee and hip bend slightly to land softly in a controlled fashion	Peak Right Knee Flexion	0.45 [-0.04, 0.76]
	Peak Right Hip Flexion	0.62 [0.2, 0.85]*
Single-Leg Sideways Hop and Hold+ - Knee and hip bend slightly to land softly in a controlled fashion	Peak Right Knee Flexion	0.77 [0.45, 0.91]*
	Peak Right Hip Flexion	0.7 [0.34, 0.89]*
Two-to-One Hop and Hold+ - Knee and hip bend slightly to land softly in a controlled fashion	Peak Right Knee Flexion	0.56 [0.11, 0.82]*
	Peak Right Hip Flexion	0.52 [0.06, 0.8]*
90-Degree Jump and Hold+ - Knee and hip bend slightly to land softly in a controlled fashion	Peak Right Knee Flexion	0.65 [0.24, 0.86]*
	Peak Right Hip Flexion	0.33 [0.18, 0.7]

rpb = Point Biserial Correlation Coefficient; +Values presented only for the right leg; *p values lower that 0.05.

Frontal plane kinematics were focused on the hip adduction and knee abduction peak angles. Positive correlation coefficients between the evaluation criteria and peak knee abduction angle ranged between 0.21 and 0.84. Correlation coefficients between the evaluation criteria and peak hip adduction ranged between -0.01 and 0.41. All correlations coefficients with confidence intervals and statistical significance can be found in table 4.

Table 4. Point Biserial Correlation Coefficients to Test the Concurrent Validity of the ChildFIRST Evaluation Criteria in the Frontal Plane.

ChildFIRST Evaluation Criterion	Biomechanical Outcome	rpb [95%CI]
Bodyweight Squat - Hips, knees, and ankles aligned	Peak Left Knee Abduction	0.69 [0.31, 0.88]*
	Peak Right Knee Abduction	0.21 [-0.3, 0.63]
	Peak Left Hip Adduction	0.41 [-0.09, 0.75]
	Peak Right Hip Adduction	0.23 [-0.28, 0.64]
Vertical Jump - Hips, knees, and ankles aligned	Peak Left Knee Abduction	0.45 [-0.04, 0.76]
	Peak Right Knee Abduction	0.38 [-0.13, 0.73]
	Peak Left Hip Adduction	0.29 [-0.22, 0.68]
	Peak Right Hip Adduction	0.24 [-0.27, 0.64]
Horizontal Jump - Hips, knees, and ankles aligned	Peak Left Knee Abduction	0.27 [-0.25, 0.66]
	Peak Right Knee Abduction	0.69 [0.32, 0.88]*
	Peak Left Hip Adduction	0.46 [-0.02, 0.77]
	Peak Right Hip Adduction	0.06 [-0.44, 0.52]
Walking Lunge - Hips, Knees, and ankles aligned	Peak Left Knee Abduction	0.36 [-0.14, 0.72]
	Peak Right Knee Abduction	0.59 [0.15, 0.83]*
	Peak Left Hip Adduction	0.3 [-0.21, 0.68]
	Peak Right Hip Adduction	0.15 [-0.36, 0.59]
Leaping -Hip, knee, and ankle aligned	Peak Left Knee Abduction	0.28 [-0.23, 0.67]
	Peak Right Knee Abduction	0.63 [0.22, 0.85]*
	Peak Left Hip Adduction	-0.01 [-0.49, 0.47]
	Peak Right Hip Adduction	0.19 [-0.32, 0.62]
Single-Leg Hop^{+} - Hip, knee, and ankle aligned	Peak Right Knee Abduction	0.84 [0.61, 0.94]*
	Peak Right Hip Adduction	0.18 [-0.33, 0.61]
Single-Leg Sideways Hop and Hold^{+} - Hip, knee, and ankle aligned	Peak Right Knee Abduction	0.79 [0.5, 0.92]*
	Peak Right Hip Adduction	0.31 [-0.2, 0.69]
Two-to-One Hop and Hold^{+} - Hip, knee, and ankle aligned	Peak Right Knee Abduction	0.74 [0.4, 0.9]*
	Peak Right Hip Adduction	0.0 [-0.48, 0.48]
90-Degree Jump and Hold^{+} - Hip, knee, and ankle aligned	Peak Right Knee Abduction	0.74 [0.41, 0.9]*
	Peak Right Hip Adduction	0.47 [-0.01, 0.78]

rpb = Point Biserial Correlation Coefficient; $^{+}$Values presented only for the right leg; *p values lower that 0.05

3.4.2 Convergent Validity

We observed positive correlation coefficients between the three movement skills from the TGMD3 and the ChildFIRST (Table 5). Similarly, we observed positive correlation coefficients between the composite score of the dynamic balance skills in the ChildFIRST and mSEBT normalized scores (Table 5).

Table 5. Spearman Rank Correlation Coefficients to Test the Convergent Validity of the ChildFIRST.

ChildFIRST	Other Tests	r [95% CI]
Horizontal Jump	TGMD-3 - Horizontal Jump	0.74 [0.4, 0.9]*
Running	TGMD-3 - Running	0.71 [0.36, 0.89]*
Single-Leg Hop	TGMD-3 - Single-Leg Hop	0.66 [0.36, 0.89]*
Composite Score	TGMD-3 - Composite Score	0.82 [0.56, 0.93]*
Dynamic Balance - Composite Score	Norm. mSEBT Composite - Right	0.83 [0.58, 0.94]*
Dynamic Balance - Composite Score	Norm. mSEBT Composite - Left	0.87 [0.67, 0.95]*

r = Spearman Rank Correlation Coefficient; *p values lower than 0.05

3.5 Discussion

This study aimed to test the concurrent and convergent validity of the ChildFIRST for 8-12-year-old children. We observed positive correlation coefficients between peak joint angles in the frontal and sagittal planes and the evaluation criteria in nine out of ten movement skills in the ChildFIRST. The only movement skill that presented negative correlation coefficients was leaping. We also observed positive correlation coefficients between specific movement skills in the ChildFIRST and the TGMD-3 and the normalized mSEBT composite scores for each leg. Our findings suggest that the ChildFIRST has the potential to identify abnormal lower limb joint motion and alignment in the frontal and sagittal planes for nine of its ten movement skills;

moreover, the ChildFIRST can be used to evaluate movement competence for locomotion and dynamic balance.

3.5.1 Concurrent Validity

Previous studies tested the validity of observational instruments and techniques using 3D motion analysis (Maclachlan et al., 2015; Onate et al., 2010; Whatman et al., 2013). Maclachlan et al., (2015) conducted a systematic review and concluded that validity studies for observational instruments that use 3D motion analysis are necessary as motion analysis systems can be expensive, resource dependant, and time-consuming (Maclachlan et al., 2015). Indeed, 3D or 2D motion analysis are not feasible for in-field contexts in which groups between 20-40 children need to be evaluated, which is one of the targets of the ChildFIRST (Maclachlan et al., 2015).

We tested the concurrent validity of 18 evaluation criteria that focus on the process of lower limb movement. We selected those evaluation criteria because the risk of musculoskeletal injury and the level of movement competence in PA and sports may depend on the quality of lower limb motion and alignment (.e.g., dynamic knee valgus) (Maclachlan et al., 2015). Although anatomical variance must be considered, certain dynamic lower limb movement patterns are potential risk factors to non-contact musculoskeletal lower limb injuries including ACL and patellofemoral syndrome (Hewett et al., 2005; Maclachlan et al., 2015; McLean, Walker, Ford, et al., 2005). One of these risk factors is poor lower limb dynamic alignment leading to a dynamic valgus, which is described as the combination of excessive pelvic drop, hip adduction and internal rotation, knee abduction, tibial internal or external rotation and foot hyper pronation (Hewett et al., 2005; Whatman et al., 2013). We focused our analysis on the hips and knees as the ChildFIRST allows for a limited observation time, and raters may tend to focus on the evaluation criteria related to noticeable movement patterns in the hips and knees.

When observing the correlation coefficients between the evaluation criteria and the lower limb peak angles in the frontal and sagittal planes we identified trends that are worth discussing. The peak knee angles correlate better with the evaluation criteria compared to the peak hip angles (Tables 3 and 4). Although the evaluation criteria “Push the hips back and bend the knees until the thighs are approximately parallel with the ground,” “Hips, knees, and ankles aligned,” and “Knees and hips bend to land softly in a controlled fashion” intend to identify motion in both the knee and hip joints in most movement skills in the ChildFIRST, raters may strongly focus on the knee when testing the participants. Thus, despite the correlation values for the evaluation criteria associated to both frontal and sagittal planes are not excellent for the hip, the evaluation criteria are sensitive enough to properly detect abnormal knee motion and alignment.

Single-legged movement skills present higher correlation values when compared with data for lower limb alignment in both the sagittal and frontal planes. The execution speed for single-legged movement skills tends to be slower than other skills, so they may be easier to assess clinically via observation (Whatman et al., 2013). Moreover, single-legged skills offer the opportunity to assess one leg at the time, which allow comparison of sides. In bilateral tasks, dynamic knee motion and alignment may not be symmetrical, and we observed that correlation coefficients are commonly higher for one knee compared to the other; suggesting, that raters focus on the knee in which they first observed the abnormal motion, which may be absent on the other knee.

Our data indicate that leaping is not valid to identify abnormal joint motion through observation using the ChildFIRST evaluation criteria. We suggest omitting the evaluation of leaping when using the ChildFIRST as other movement competence instruments, such as the TGMD-3 and the Canadian Agility and Movement Skill Assessment (CAMSA), for the same age do not include leaping (Hulteen et al., 2020; Longmuir et al., 2017; Webster & Ulrich, 2017). Moreover, although the technique and underlying coordination of leaping differs from other movement skills included in the ChildFIRST, we can obtain useful information from movement skills like single-leg hop, Two-to-one foot hop and hold, which share similar movement patterns. Streamlining the ChildFIRST will enhance its feasibility and practicability, especially in groups above 30 children.

3.5.2 Convergent Validity

The ChildFIRST has convergent validity when compared to the TGMD-3 and the mSEBT. Convergent validity alongside discriminant validity are the two main forms of construct validity. Discriminant validity concerns whether correlations between the scores from two tools that measure different constructs are sufficiently low (Kline, 2008). We did not test discriminant validity because we could not find a comparable test that measured a different construct. Furthermore, although we did not test the construct validity of the ChildFIRST using confirmatory and/or exploratory factor analysis, we tested the convergent validity by comparing the ChildFIRST against assessment tools that had been validated through appropriated means (Coughlan et al., 2012; Hulteen et al., 2020; Webster & Ulrich, 2017). For instance, the factor structures of the TGMD-3 are well-supported with quantitative evidence (Hulteen et al., 2020). Our results indicate that specific movement skills in the ChildFIRST and the TGMD-3 have related results. Similarly, we observed that the movement skills that aim to assess dynamic balance in the ChildFIRST had related results when compared to the normalized mSEBT scores for each limb.

Although the correlation coefficients between mSEBT and the dynamic balance skills is high for the right (0.83 [0.58, 0.94]) and left (0.87 [0.67, 0.95]) legs, we noticed that only one dynamic balance movement skill (i.e., single-leg sideways hop and hold) has a postural stability oriented evaluation criterion (i.e., stand up straight within three seconds after landing). The correlation coefficients may not reflect the actual capacity of the other two movement skills (i.e., two-to-one foot hop and hold and 90-degree hop and hold) to identify lack of balance/postural stability. All dynamic balance skills in the ChildFIRST have evaluation criteria related to movement competence and injury risk, which is still relevant considering that all three skills require that the participants regain postural stability after landing from a previous movement.

3.5.3 ChildFIRST Implications

The ChildFIRST aims to be a feasible and practical instrument that can be used in PA- and sports-related settings (Jimenez-Garcia et al., 2020; Miller et al., 2020). Establishing the concurrent and convergent validity of the ChildFIRST can help researchers and practitioners to identify children who present poor movement competence and are at increased risk of lower limb injury. PA-related injuries are considered as threats to school-aged adolescents in many countries; for example, sports and leisure activities were associated with at least 39% of fractures in children and adolescents (Cai et al., 2018; Hedström et al., 2010). Musculoskeletal injuries may cause periods of absence from school, contribute to the childhood obesity epidemic, and prevent individuals from participating in PA and organized sports (Costa e Silva et al., 2017). Moreover, after a musculoskeletal injury happens, individuals may face decreased confidence and willingness to do PA because of the negative perception and fear of injury (Siesmaa et al., 2011). The significance of the aforementioned situations depends on the place and severity of the injury, which reveals the utility and necessity of the early identification of individuals at increased risk of musculoskeletal injury. Identifying individuals with poor movement competence and increased risk of injury using the ChildFIRST can help to target interventions to reduce the risk of suffering the first injury in children's lives and could result in increased PA and sports participation.

Validating the movement competence construct of the ChildFIRST confirms its suitability in different contexts. For example, although the ChildFIRST only considers the physical factor of the physical literacy model, incorporating an injury prevention approach to physical literacy assessments benefits the promotion of safe lifelong PA (Jimenez-Garcia et al., 2020; Miller et al., 2020). The assessment of movement skills including squats, single-legged tasks, and bilateral jumps may be used to evaluate an individual's injury risk and direct the content of preventative/performance programs. Although this study indicates a relationship between the ChildFIRST and evaluation criteria associated with movement patterns that, when faulty, may be risk factors for musculoskeletal injuries, we cannot state an evidence-based connection between the ChildFIRST and injury risk and incidence in childhood. Future longitudinal studies should establish the connection between the ChildFIRST and musculoskeletal injuries to test its sensitivity and specificity. Considering that physical literacy interventions, sport practices, and physical education classes are movement-based in nature, we suggest that the ChildFIRST can be used in pre-screening and evaluation processes to provide practitioners with useful information to tailor the interventions based on the children's movement capacities and needs. Pre-screening was recommended by Padua et al., (2015) and Hewett et al., (2005), who reported positive results after the modification of the intervention based on the categorization of groups by the participants' injury profile (Hewett et al., 2005; Padua et al., 2015).

3.5.4 Limitations

The results of this study should be interpreted carefully due to some limitations. We had a small sample size (n=17) and conducted multiple comparisons that may affect the power of this study; however, we determined the sample size using an *a* priori power analysis. Moreover, the cost of each testing session obligated the researchers to recruit the minimum number of participants obtained through this power analysis. Most participants were nine years old or older, which resulted in an underrepresentation of eight-year-olds. The proportion of male participants (82.35%) is significantly higher compared to females. Since we were not studying sex differences and used convenience sampling, we did not balance the sample based on sex. The generalization of this study may be compromised because characteristics and size of our sample.

Our results are strongly influenced by the skill-level and experience of the investigators. However, we conducted training using all the physical tests and the 3D motion analysis system. Although we used a standardized marker placement that was done by the same investigator for all participants, the variability in the trials was unavoidable due to marker placement error and variations in posture. We did not test the concurrent validity of all the ChildFIRST evaluation criteria. The comparison between some evaluation criteria and kinematic analysis was not feasible. Furthermore, we focused on lower limb injuries, which are commonly observed in PA and sports (Emery, 2010; Meeuwisse et al., 2007; Miller et al., 2018). However, we did not include any ankle data, which would complement the hip and knee data.

3.6 Conclusions

Our study provides empirical evidence for the concurrent and convergent validity of the ChildFIRST. The concurrent validity of the evaluation criteria on the ChildFIRST that focus on lower limb motion and alignment in the frontal and sagittal planes is supported by moderate ($r >$

0.3) to excellent ($r > 0.8$) correlation values for nine out of the ten movement skills. The only movement skill that presented negative correlation values was leaping, which compromises its validity. The movement skills running, single-leg hop, and horizontal jump presented excellent correlation values when compared to the TGMD-3 results, supporting their convergent validity. Similarly, the movement skills single-leg sideways hop and hold, two-to-one foot hop and hold, and 90-degree jump and hold presented excellent correlation values when compared to the normalized composite scored of the mSEBT. The ChildFIRST has the potential to identify abnormal lower limb joint motion and alignment in the frontal and sagittal planes and should be used in pre-screening processes to tailor the interventions based on the children’s movement capacities and needs. For example, if children do not meet the evaluation criteria for lower limb alignment, interventions could attempt to improve these shortcomings by using specific feedback on the movement performance. Adding an injury prevention approach to traditional movement competence assessment can help promote safe PA by identifying individuals with poor movement competence and higher injury risk.

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Conflict of Interest Statement

The first (JJ) and third author (RD) participated in the development, validation, and the reliability testing of the Child Focused Injury Risk Screening Tool (ChildFIRST).

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Transition to Chapter Four

We provided concurrent and convergent validity evidence for the ChildFIRST in chapter three. Chapter four describes the testing of the feasibility and effects of a novel neuromuscular warm-up that aimed to advance in the promotion of safe physical activity (PA) by enhancing physical literacy construct and neuromuscular training and reducing the risk of lower-limb musculoskeletal injuries. We used the ChildFIRST to evaluate the effects of the neuromuscular warm-up in 8-12-year-old children's movement competence and injury risk profile.

The manuscript presented in chapter four was submitted to *Pediatric Exercise Science*.

Chapter Four: Manuscript Three

Feasibility and Outcomes of a Neuromuscular Warm-Up based on the Physical Literacy Model and Injury Prevention Strategies for 8-12-Year-Old Children

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Note: The manuscript in chapter three has the referencing style required by *Pediatric Exercise Science*. We kept this format to maintain the integrity of the manuscript. No content has been modified.

4.1. Abstract

Background. Physical literacy and injury prevention strategies use similar movement-related constructs and can be connected to develop comprehensive interventions. We aimed to test the feasibility and effects of a neuromuscular warm-up based on physical literacy and injury prevention strategies for 8-12-year-old children. ***Methods.*** We conducted a cluster non-randomized controlled trial. We defined *a priori* feasibility criteria and studied the effects of the intervention on physical literacy constructs, movement competence, and neuromuscular performance. We used generalized linear mixed models controlling for covariates and clustering with a significance level of 0.001. ***Results.*** We recruited 18 groups (n=363) and randomly allocated nine to intervention (n=179; female=63.7%, age=9.8±1) and nine to control (n=184, female=53.3%, age=9.9±0.9). We met four of seven feasibility criteria (i.e., recruitment, adherence, enjoyment, perceived exertion). The three feasibility criteria that were not met (i.e., compliance, fidelity, follow-up) were slightly below the predefined threshold (90%). Model-adjusted mean differences for physical literacy constructs, movement competence, vertical jump, horizontal jump, 20m sprint, and dynamic balance favored the intervention ($p<0.001$). ***Conclusion.*** The feasibility evidence indicates that the intervention should be slightly modified before implementing it in a larger study. The observed effect sizes are promising and can be used in planning future interventions.

Keywords: *children, neuromuscular training, physical literacy, injury prevention, feasibility*

4.2. Introduction

Promoting physical activity (PA) in youth is a worldwide goal in various contexts, such as schools, sports teams, and clinics (46). The World Health Organization and national public health institutes have developed a series of guidelines that suggest children engage in PA for a minimum of 60 minutes daily while reducing their screen and sitting times (43, 46). Those 60 minutes should primarily consist of aerobic exercises and include movements that strengthen muscles and bones (46). However, promoting PA and maintaining the recommended PA levels can be challenging due to different factors such as culture, setting, and individual characteristics (39). Stakeholders have worked to find the most effective ways to promote and maintain PA in youth, and physical literacy has been proposed as a mean towards promotion of lifelong PA (45). The physical literacy model encompasses a holistic approach that considers four domains: affective, cognitive, behavioral, and physical (45). In a physical literacy framework, individuals value and take responsibility for engagement in lifelong PA through motivation, confidence, physical competence, knowledge, and understanding (6). Physical literacy is highly individual, can be cultivated through experiences, and can be nurtured through life, which contribute to the development of the whole person in a PA context (6, 7, 14).

Promoting PA in youth is fundamental, and although most children safely participate in PA, there is an inherent risk of musculoskeletal injury (23). Evidence indicates that between 0.43 injuries can occur among children per 1000h of moderate to vigorous PA (23, 25). Musculoskeletal injuries can lead to pain, fear of injury or movement, or surgery that could prevent children's PA involvement and may lead to sedentary behavior and increased screen time (38). Parents may also restrict their children's PA participation due to worries about the risk of potential injuries (5).

Injury prevention strategies focus on reducing the risk of musculoskeletal injuries (15, 22, 32). A variety of Multicomponent Injury Prevention Programs (MIPP) target the lower limbs, which make up 66% of all sports-related injuries (32). MIPP encompasses various components like strength, power, agility, flexibility, and balance, which can work together to reduce injury risk (30, 32). Meta-analytical data suggest that MIPP lasting between 15-20 minutes may provide sufficient stimuli for positive changes in biomechanical and neuromuscular performance in children and adolescents (22). Moreover, MIPP in the form of neuromuscular warm-ups may be practical and feasible as they do not require extra time from the participants and stakeholders (18, 32, 33). Evidence indicates that developmentally appropriate MIPP effectively reduces approximately 46% of musculoskeletal injuries (37). Furthermore, neuromuscular performance and movement competence can also be positively affected by comprehensive MIPP (22, 37). Given that movement competence is hypothesized to be associated with PA, weight status, perceived movement competence, and fitness, MIPP could also have the potential to enhance PA promotion processes (41). Unfortunately, MIPP are primarily conducted in sport-related settings, and other contexts (e.g., physical literacy interventions, physical education (PE) classes) may not benefit from their implementation (22).

Developing an intervention that combines the theoretical constructs of the physical literacy model with the practical features of MIPP may help promote safe PA by inducing positive effects in the affective, cognitive, and physical domains of the physical literacy model and reduce the risk of musculoskeletal injury. Children aged 8 to 12 may particularly benefit from this type of intervention as they experience growth and maturation processes that can impact their movement competence, PA levels, and risk of musculoskeletal injuries (12). The potential intervention should incorporate the methodological characteristics and extensive evidence of MIPP and the holistic approach of a physical literacy framework (6, 7, 33). However, investing resources in a novel intervention may only be supported with evidence that it would be effective in targeted contexts (13).

Feasibility studies help determine whether an intervention could be successful (31). Studying the feasibility of an intervention would lead to identifying barriers and facilitators, which is fundamental for implementing MIPP, physical literacy programs, and organized PA (22, 33). Evaluating the intervention safety, determining the ideal dose response, and obtaining preliminary effectiveness evidence are also crucial steps in planning future studies (13, 31). Other components (e.g., recruitment strategy, adherence, compliance, acceptance, fidelity) that affect the effectiveness of the intervention should also be evaluated before investing further resources (33).

The physical literacy model and MIPP use similar theoretical constructs and movement skills, yet their connection in the literature is limited, and as far as we know, no intervention has been developed by combining these fields (27, 47). To bridge the gap between the physical literacy model and MIPP, we developed a 15-minute neuromuscular warm-up based on the affective and cognitive domains of the physical literacy model, four components of MIPP (i.e., strength, plyometrics, agility, and balance), and movement skills for 8-12-year-old children. The objectives of this study were twofold: First, to test the feasibility of the neuromuscular warm-up and assessment protocol for 8-12-year-old children in a school setting. Second, to explore the effects of the neuromuscular warm-up in physical literacy constructs (i.e., affective, cognitive, physical), neuromuscular performance, and musculoskeletal injury risk profile in 8-12-year-old children.

4.3. Methods

4.3.1. Experimental Design

We conducted a cluster non-randomized controlled trial in two schools in Colombia. This study was approved by a University Human Research Ethics Committee in Canada that considered its multijurisdictional nature. We followed the CONSORT checklist with the extension for cluster designs to prepare and report this study (9). We translated and reverse-translated all instructions and assessments that were not originally developed or validated in Spanish (34, 44).

4.3.2. Clusters and Participants

The target clusters were 3rd, 4th, and 5th grades. The inclusion criteria for the participants were: Children who: (a) were injury-free; (b) were officially enrolled in a school in 3rd, 4th, and 5th grades; and (c) were aged between 8 and 12 years. The exclusion criteria for the participants were: Children who: (a) lived with overweight or obesity, which was determined by age/sex-specific body mass index (BMI). We calculated BMI (weight (Kg) / height (m^2)) and compared it against the Centers for Disease Control and Prevention (CDC) growth charts (20). We adopted the CDC classification (overweight between the 85th and the 95th percentile and obesity above the 95th percentile) (11); (b) reported injuries for six weeks before testing; (c) reported any recurrent injury that kept them from participating in PA for more than 30 days in the past year; (d) are in post-operative rehabilitation; (e) live with a cognitive impairment reported by parents; and (f) were not aged between 8 and 12 years. Neither the participants nor the schools received any compensation (i.e., economic, academic) for participating in any stage of this intervention.

4.3.3. Sample Size, Recruitment, and Randomization

We used convenience sampling to recruit the children from the schools. We presented the study to the staff at the schools to obtain approval and recruit participants. After obtaining permission, all parents/guardians provided signed consent, and children verbally assent to participate in our study.

An independent researcher from a laboratory with no relationship with the authors generated random numbers to allocate the groups to either the intervention or control conditions. The groups were block-randomized (1:1) at the grade level. Although we did not calculate the sample size based on *a priori* power analysis that controlled for clustering, we recruited the as many groups and participants as possible to test the feasibility of the recruitment strategy, the assessment protocol, and the intervention in multiple groups at different schools.

4.3.4. Intervention

Intervention Group. Based on theory and evidence, we determined the practical elements of the intervention to achieve clinically meaningful results (6, 7, 33). The physical literacy model was the theoretical foundation of all intervention elements (6, 10). We developed and delivered a neuromuscular warm-up based on four components of MIPP (i.e., strength, balance, agility, and plyometrics) (22), fundamental movement skills (i.e., locomotion and balance), and basic movement patterns (e.g., bodyweight squat, lunges). We accounted for the affective and cognitive factors of the physical literacy model by using positive reinforcement, augmented feedback (i.e., knowledge of result/performance), peer interactions, and PA-related messages (Appendix 1) (42). We used external focused cues to favor the movement skill acquisition process and actively provided feedback to enhance participants' confidence, motivation, and self-efficacy (3, 42). The methodological elements of the intervention can be found in Figure 1 and the content of the neuromuscular warm-up can be found in Table 1.

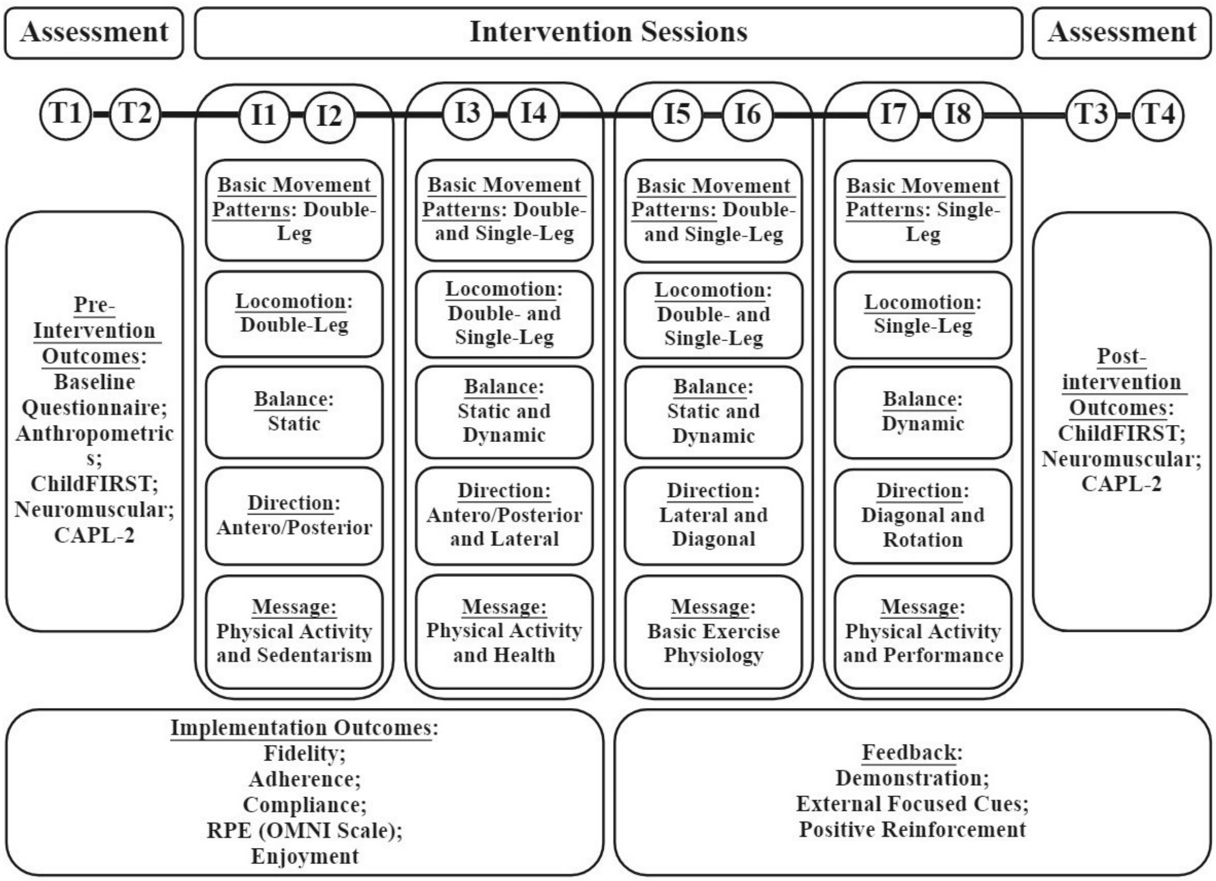

Figure 1. Rationale and distribution of the assessment and intervention sessions. ChildFIRST = Child Focused Injury Risk Screening Tool; CAPL-2 = Canadian Assessment of Physical Literacy 2; RPE = rate of perceived exertion.

Table 1. Content of the Neuromuscular Warm-up

Session	Movement Skills	Attentional Cues
1	Running (2 x 20m)	Run like you are a soldier marching!
	Bodyweight Squat (2 x 10)	Imagine you are a frog squatting!
	Walking Lunge (2 x 10m)	Imagine you are stepping onto a platform!
	Vertical Jump (2 x 10)	Imagine you are landing on eggshells!
	Horizontal Jump (2 x 10)	Jump like a frog!
	Single-Leg Balance (2 x 30s)	Pretend you are balancing on a tightrope!
2	Running Forward/Backward (2 x 20m)	Run like you are a soldier marching!
	Skipping (2 x 20m)	Imagine you are running through a field of tall grass!
	Bodyweight Squat (2 x 10)	Imagine you are sitting down in a chair!
	Walking Lunge (2 x 10m)	Imagine you are stepping onto a platform!
	Horizontal Jump (2 x 10)	Land like a cat!
	Airplane Balance (2 x 30s)	Pretend you are balancing on a tightrope!
3	Skipping Forward/Backward (2 x 20m)	Imagine you are running through a field of tall grass!
	Bodyweight Squat (2 x 10)	Imagine you are sitting down in a chair!
	Walking Lunge Forward/Backward (2 x 10m)	Imagine you are stepping over an obstacle!
	Vertical Jumps (2 x 10)	Imagine you are landing on eggshells!
	Single-Leg Hop (2 x 10m)	Pretend you are tracing a line with your foot!
	Airplane Balance (eyes closed) (2 x 30s)	Pretend you are balancing on a tightrope!
4	Skipping Forward/Backward (2 x 20m)	Imagine you are running through a field of tall grass!
	Bodyweight Squat (1 x 10)	Keep a proud chest and your back straight!
	Single-Leg Hip Hinge (2 x 10)	Imagine you are reaching for something on the ground with your hand!
	Vertical Jump (2 x 10)	Swing your arms towards the sky when jumping!
	Lateral Single-Leg Hop (2 x 10)	Pretend you are tracing a line with your foot!

	Single-Leg balance after a forward Jump (2 x 30s)	Imagine you are balancing a ball on your head!
5	Lateral Skipping (2 x 10m)	Imagine you are running through a field of tall grass!
	Bodyweight squat (1 x 10)	Keep a proud chest and your back straight!
	Single-Leg Squat (2 x 10)	Imagine you are sitting down in a chair!
	Walking Lunge Forward/Backward (2 x 10m)	Imagine a laser beam shooting out of your knee and point it ahead!
	Tuck Jump (2 x 10)	Imagine you are landing on a cloud!
	Single-Leg Balance after a forward jump (2 x 30s)	Imagine you are balancing a ball on your head!
6	Diagonal Running (2 x 20m)	Run like you are a soldier marching!
	Bodyweight Squat (1 x 10)	Push your knees out towards the wall!
	Single-Leg Squat (2 x 10)	Imagine a laser beam shooting out of your knee and point it ahead!
	Single-Leg Hip Hinge (2 x 10)	Imagine you are reaching for something on the ground with your hand!
	Single-Leg Hop for height (2 x 10)	Imagine you are pushing the ground away with your foot!
	Single-Leg Balance after a lateral jump (2 x 30s)	Imagine you are balancing a ball on your head!
7	Diagonal Skipping (2 x 20m)	Imagine you are running through a field of tall grass!
	Bodyweight Squat (1 x 10)	Push your knees out towards the wall!
	Single-Leg Hip Hinge (2 x 10)	Imagine you are reaching for something on the ground with your hand!
	Single-Leg Hop for height (2 x 10)	Imagine you are pushing the ground away with your foot!
	Single-Leg Hop for distance (2 x 10)	Imagine a laser beam shooting out of your knee and point it ahead!
	Single-Leg Balance after a diagonal Jump (2 x 30s)	Imagine you are balancing a ball on your head!

8	Diagonal Skipping (2 x 20m)	Imagine you are running through a field of tall grass!
	Single Leg Squat (2 x 10)	Imagine a laser beam shooting out of your knee and point it ahead!
	Single-Leg Hip Hinge (2 x 10)	Stand up tall at the top!
	Single-Leg Hop for height (2 x 10)	Swing your arms towards the sky when jumping!
	Single-Leg Hop for distance (2 x 10)	Imagine you are landing on a cloud!
	Single-Leg Balance after a 90-degree Jump (2 x 30s)	Imagine you are balancing a ball on your head!

The neuromuscular warm-up consisted of two 15-minute sessions per week over four weeks (n = 8 sessions). Two trained facilitators led the sessions. We replaced the warm-up routine for the intervention group. A session was composed of a PA-related message, and a movement skills practice based on different MIPP components and peer interactions. The design of the intervention included the aspects of movement, affective, and social constructs as described by Carney et al. (2019) (7). The level of difficulty of the movement skills was progressed throughout the intervention (Figure 1) as suggested by the literature (29, 32, 33). The information and cues were standardized across groups (Table 1). No extra time was expended by the PE teachers; however, the teachers were present in the sessions.

Comparison Group. We used a comparison group that received their regular warm-up routine based on jogging and static stretching. The control group did not received feedback on movement technique or any PA-related message.

4.3.5. Feasibility and Implementation Evaluation

The *a priori* feasibility criteria for the intervention can be found in Table 2. In the intervention group, we evaluated the implementation using adherence, compliance, rate of perceived exertion (RPE), enjoyment, follow up, and fidelity. In the control group, we only evaluated adherence. We measured adherence using the attendance. We measured compliance based on the facilitator's perception about children's compliance with the intervention. We measured RPE using the OMNI scale, whose scores range between zero and ten, with zero being extremely easy and ten extremely hard (36). We measured enjoyment using an original 5-point emoji scale (i.e., the intervention was: (1) Boring; (2) Somewhat Boring; (3) Neither Boring nor Fun; (4) Somewhat Fun; (5) Fun).

Table 2. Feasibility Criteria

Criteria
Recruit 12 groups (6 per school, 2 for each grade to allow comparability)
Maintain > 90% of adherence
Maintain > 90% of compliance
Maintain > 90% of fidelity
> 90% of participants scored the intervention as fun (> 4 in the scale)
Obtain an RPE average < 5 points in the OMNI scale(36)
Collect data in > 90% of the participants at baseline and follow up

RPE = rate of perceived exertion

We measured fidelity of the intervention by averaging four equally weighted variables (i.e., delivery of the content, delivery of the message, use of feedback, and time to complete the session) collected through an original, self-reported, and scale-based checklist. We measured the delivery of content using a three-point scale (i.e., (1) not accomplished, (2) partially accomplished, (3) accomplished). We measured the delivery of the message based on the number of messages delivered in the session (i.e., 0 = no message delivered, 1 = message delivered once, 2 = message delivered twice). We measured the use of feedback using the same three-three point scale as delivery. We evaluated the time to complete the session using the following scores: three points if the session lasted 15 minutes or fewer, two points if the session lasted between 15 and 16.5 minutes, and one point if the session lasted more than 16.5 minutes. The facilitator reported the reason why the fidelity was compromised when necessary.

4.3.6. Outcome Measures

The assessors were six blinded and trained 3rd year college students from a sports science program. The assessors received five training sessions including video and in-field practices. We controlled for environmental influences by conducting the assessments on the same place and surface using standardized procedures. The assessment process was divided into two-hour sessions for a total of four testing sessions when combining pre-intervention (n = 2) and post-intervention (n = 2) assessments. We asked the children whether they suffered from pain or discomfort before the assessment sessions.

The participants and their parents/guardians completed a demographic questionnaire (i.e., age, sex as a biological variable, injury history, PA history) and the Spanish version of the Canadian Assessment of Physical Literacy 2 (CAPL2) at home (34). We used the CAPL2 to assess the affective and cognitive domains of the physical literacy model (24). We explained the children how to complete the CAPL2 and shared a manual with the parents/guardians. In the first assessment session, we measured participants' anthropometrics using a portable stadiometer (SECA Model 2013, Chino, CA) and a portable scale (SECA model 813, Chino, CA) using standard procedures (26). Moreover, the participants completed the Child Focused Injury Risk Screening Tool (ChildFIRST) to assess movement competence and quality (21, 28). The ChildFIRST is a process-based movement competence assessment tool that is consists of ten movement skills each with four evaluation criteria (21). The ChildFIRST aim to identify children with poor movement competence and increased risk of lower limb musculoskeletal injury using dichotomous scores for each evaluation criterion and a composite score of maximum 40 points (21, 28). A low score in the ChildFIRST indicate poor movement competence and increased risk of musculoskeletal injury. In the second assessment session, the participants completed the following physical tests: vertical jump (Abalakov's vertical jump test), horizontal jump, 20m sprint test, and the modified Star Excursion Balance Test. All the tests and instruments used on this study have been described, validated, and tested for reliability elsewhere (1, 8, 19, 21, 24, 28).

4.3.7. Procedures

Each session aimed to last 15 minutes or fewer. The facilitator started the session by delivering a PA-related message, which was repeated at the end of the session. Then, the children completed a series of movement skills. After completing the session, the facilitator asked the children for their RPE and enjoyment level for that specific session. The facilitator used a series of standardized external focused cues and feedback during the intervention.

4.3.8. Statistical Analysis

We used R (Version 4.2.2) (35) and the library (lme4) (2) to conduct the statistical analysis. We reported pre- and post-intervention descriptive statistics. We conducted exploratory data analysis to identify any missing data, outliers, or imputation mistakes. We checked different assumptions to select the statistical tests and models. We based our analysis on the intention-to-treat analysis principle. Depending on the characteristics of the variables, we compared group means at baseline using t-tests or Man-Whitney U tests. We also compared proportions of the sex variable at baseline using a Chi-Squared test. We modelled the observed data using Generalized Linear Mixed Models (GLMM) with a Gaussian distribution with the Identity Link Function for continuous variables and a Poisson distribution with the Log Link Function for discrete variables (4). We set the intervention (i.e., INT or CON) as the fixed effect, the baseline scores, age, and sex as covariates, and the groups as the random effects to account for clustering.

We fitted the model using the Restricted Maximum Likelihood (REML) estimator for normally distributed variables and the Iterated Reweighted Least Squares (IRLS) estimator for non-normally distributed variables (4). We evaluated the model fit via visual inspection of residual plots. We used the fitted model estimates to perform a t-test to test the treatment effects and the intracluster correlation coefficient (ICC). We reported model-adjusted mean differences with 95% confidence intervals (CI). All statistical tests were two-sided at an 0.001 alpha level to reduce the likelihood of making type 1 error due to the absence of a sample size calculation, the potential lack of power due to the multiple comparisons, and imbalances between clusters.

4..4. Results

4.4.1. Participants Characteristics

Nine groups (participants = 179, female = 63.7%, age = 9.8 ± 1, height = 136.7 ± 8.6, weight = 31.8 ± 5.9, BMI = 16.8 ± 1.5) were allocated to the intervention group (INT) and nine groups (participants = 184, female = 53.3%, age = 9.9 ± 0.9, height = 137.9 ± 7.9, weight = 32.1 ± 5.8, BMI = 16.8 ± 1.8) were allocated to the control group (CON). We did not observe statistically significant differences in the demographic and anthropometric variables between INT and CON at baseline. All the nine groups allocated to the INT completed the study. The CONSORT diagram can be found in Appendix 2.

4.4.2. Implementation

Feasibility criteria and the proportion of criteria met can be found in Table 2. The average time (107.6 ± 5.9 min) for all assessment sessions was lower than the planned time (120 min). The average time (15.6 ± 0.7 min) for all intervention sessions was slightly higher than the planned time (15 min). We recruited six more groups (50%) than expected (n = 12). The adherence of intervention was 90.1% (range = 87.9% - 94.2%). The compliance of the intervention was 87.8% (range = 85.3% - 91.7%). The fidelity of the intervention was 86.6% (range = 83.1% - 88.3%). Participants' RPE mean was 3.36 ± 1.19, and enjoyment mean was 4.36 ± 0.76. Seven groups missed one intervention session because one school was closed on two different days, and we could not reschedule the missed sessions. Facilitators reported why the session could not be delivered as intended in 44.6% of the sessions, and the reasons were related to the children's characteristics (24.1%), the training received (17.2%), the session time (13.8%), the logistics (27.6%), and human mistakes (17.2%). Detailed information about the testing and intervention sessions can be found in Table 3.

4.4.3. Effects of the Intervention

All the variables met the assumptions for the proposed models and statistical tests. All models converged and residual plots indicated that the models fit the data. We did not have any missing data and did not identify extreme outliers that significantly deviated from the sample. The values for the 20m sprint test were statistically different ($p = 0.035$) at baseline.

All the model-adjusted mean differences favored the intervention. We observed statistically significant differences ($p<0.001$) for the CAPL2 composite score, ChildFIRST composite score, vertical jump, horizontal jump, 20m sprint, mSEBT (composite score and directions) between the INT and CON groups after controlling for baseline values, sex, age, and clustering. We also analyzed scores for individual skills in the ChildFIRST and the "confidence and motivation" and "knowledge and understanding" elements of the CAPL2. All point estimates and 95% confidence intervals can be found in Table 4.

Table 3. Descriptive and Fidelity Values of the Intervention Sessions

Group	Testing (n)	Testing Time (mean (SD))	Sessions (n)	Session Time (mean (SD))	Adherence (%)	Compliance (%)	Fidelity (%)*	RPE (mean (SD))	Enjoyment (mean (SD))
3a_int	4	110.3 (8.4)	7	15.6 (0.9)	87.8	85.3	87	3.27 (1.29)	4.19 (0.81)
3b_int	4	105.1 (6.8)	7	15.7 (0.7)	89.3	87.7	87	3.53 (1.27)	4.33 (0.80)
3c_int	4	107.6 (6.1)	7	15.7 (0.7)	90	88.3	88.3	3.48 (1.27)	4.41 (0.77)
4a_int	4	107.7 (6.9)	7	15.6 (0.7)	87.9	87.1	87	3.32 (1.16)	4.46 (0.74)
4b_int	4	109 (5.9)	7	15.7 (0.6)	89.3	86.5	83.1	3.48 (1.30)	4.54 (0.61)
4c_int	4	106 (3.5)	8	15.5 (0.6)	94.2	90.0	85.2	3.30 (1.00)	4.41 (0.68)
5a_int	4	105 (3.5)	7	15.5 (1.1)	91	86.8	87	3.45 (1.18)	4.36 (0.61)
5b_int	4	106.6 (7.4)	7	15.3 (0.6)	87.9	87.1	87	3.14 (0.98)	4.43 (0.70)
5c_int	4	111.6 (6.5)	8	15.5 (0.7)	93.3	91.7	87.5	3.20 (1.16)	4.11 (0.79)
All Groups	36	107.6 (5.9)	65	15.6 (0.7)	90.1	87.8	86.6	3.36 (1.19)	4.36 (0.76)

* RPE = rate of perceived exertion; SD = standard deviation; Fidelity was assessed only for the intervention sessions

Table 4. Point estimates, 95% confidence intervals for all outcomes

	INT pre	INT post	CON pre	CON post	model-adjusted mean difference [95%CI]	se	t-value	ICC
Vertical Jump (cm)*	19.14 (1.53)	20.08 (1.40)	19.13 (1.49)	19.05 (1.44)	1.05 [0.82, 1.28]	0.116	9.04	0.004
Horizontal Jump (cm)*	141.29 (7.03)	145.26 (9.03)	140.60 (8.59)	142.94 (7.69)	1.71 [0.88, 2.54]	0.422	4.05	0.007
20m Sprint (s)*	5.18 (0.36)	4.77 (0.30)	5.10 (0.34)	5.01 (0.35)	-0.25 [-0.37, -0.12]	0.063	-3.89	0.125
Right mSEBT (%)*	100.53 (5.64)	103.71 (5.61)	100.96 (5.13)	103.16 (5.19)	0.98 [0.79, 1.18]	0.078	12.53	0.015
Right Anterior (%)*	82 (5.18)	84.24 (5.28)	82.27 (5.91)	83.58 (60.1)	0.92 [0.65, 1.19]	0.137	6.72	0.062
Right Posterolateral (%)*	108.14 (10.47)	111.80 (10.46)	108.65 (9.97)	111.43 (10.06)	0.9 [0.68, 1.13]	0.115	7.85	0.032
Right Mediolateral (%)*	111.46 (10.17)	115.09 (10.15)	111.96 (9.51)	114.48 (9.61)	1.12[0.94, 1.30]	0.092	12.21	0.011
Left mSEBT (%)*	99.11 (4.84)	102.27 (4.82)	99.68 (4.73)	101.94 (4.82)	0.92 [0.77, 1.06]	0.073	12.55	0.012

Left Anterior (%)*	80.68 (5.91)	82.95 (5.97)	80.68 (5.12)	82.13 (5.18)	0.82 [0.64, 1.00]	0.092	8.95	0.034
Left Mediolateral (%)*	105.99 (9.15)	109.71 (9.22)	107.91 (8.52)	110.67 (8.63)	0.99 [0.76, 1.22]	0.115	8.57	0.027
Left Posterolateral (%)*	110.64 (10.58)	114.14 (10.61)	110.46 (9.52)	113.01 (9.54)	0.95 [0.79, 1.11]	0.083	11.46	0.001
ChildFIRST (composite)*	26.58 (3.92)	30.35 (3.40)	27.00 (3.92)	27.04 (3.93)	0.13 [0.09, 0.17]	0.2	19.21	0.018
Bodyweight Squat	2.78 (0.98)	3.06 (0.90)	2.72 (0.95)	2.69 (0.93)	0.11 [-0.01, 0.23]	0.062	1.8	0
Walking Lunge	2.22 (1.01)	2.82 (0.92)	2.30 (1.02)	2.34 (1.03)	0.22 [0.09, 0.35]	0.066	3.35	0
Running	3.61 (0.56)	3.74 (0.45)	3.67 (0.59)	3.59 (0.65)	0.06 [-0.05, 0.16]	0.055	1	0.001
Single-Leg Hop	2.55 (0.76)	2.96 (0.78)	2.64 (0.86)	2.65 (0.90)	0.15 [0.02, 0.27]	0.063	2.32	0
Leaping	2.63 (0.91)	3.03 (0.88)	2.73 (0.79)	2.76 (0.84)	0.12 [-0.00, 0.24]	0.062	1.92	0.006
Vertical Jump	2.56 (0.84)	2.97 (0.86)	2.63 (0.88)	2.57 (0.89)	0.17 [0.04, 0.29]	0.063	2.61	0
Horizontal Jump	2.72 (0.93)	3.01 (0.83)	2.70 (0.93)	2.74 (0.87)	0.09 [-0.04, 0.21]	0.062	1.38	0.002
Two-to-One Foot Hop and Hold	2.58 (0.91)	2.93 (0.84)	2.34 (1.01)	2.38 (0.98)	0.14 [0.02, 0.27]	0.065	2.21	0
Single-Leg Sideways Hop and Hold	2.53 (0.89)	2.96 (0.81)	2.66 (0.85)	2.70 (0.91)	0.13 [0.00, 0.25]	0.063	2.04	0
90-degree Jump and Hold	2.40 (0.93)	2.85 (0.85)	2.61 (0.98)	2.63 (0.97)	0.15 [0.02, 0.28]	0.064	2.33	0.001
CAPL2 (composite)*	29.12 (3.54)	32.14 (2.42)	28.37 (3.21)	29.25 (2.82)	2.49 [2.05, 2.93]	0.225	11.07	0.007
Motivation and Confidence*	23.24 (2.89)	24.27 (1.94)	22.85 (2.73)	23.58 (2.27)	0.44 [0.22, 0.67]	0.115	3.85	0.006
Knowledge and Understanding*	5.88 (1.75)	7.87 (1.37)	5.52 (1.59)	5.67 (1.74)	0.32 [0.24, 0.40]	0.041	7.72	0.010

* Statistically significant differences ($p < 0.001$); INT = Intervention Group; CON = Control Group; se = Standard Error; ICC = Intracluster Correlation Coefficient; mSEBT = Modified Star Excursion Balance Test; ChildFIRST = Child Focused Injury Risk Screening Tool; CAPL2 = Canadian Assessment of Physical Literacy 2.

4.5. Discussion

This study had two objectives. The first objective aimed to test the feasibility of a neuromuscular warm-up and assessment protocol for 8-12-year-old children in an elementary school setting. We did not achieve all the *a priori* defined feasibility criteria. We observed positive results for the recruitment process, adherence, enjoyment, and RPE. In contrast, compliance, fidelity, and the follow up were slightly below the predefined threshold, which may raise concerns about the impact these variables have on the effectiveness of any intervention (22, 33). Our findings indicate that the neuromuscular warm-up has an appropriate intensity as observed via the RPE and is well accepted based on the participants' enjoyment scores. The assessment protocol was feasible in terms of time, enjoyment, and intensity. Making slight modifications could increase the likelihood of success of a multisite intervention with a complex experimental design.

The second objective aimed to explore the effects of the warm-up in physical literacy constructs (i.e., affective, cognitive, physical), neuromuscular performance, and injury risk profile in 8-12-year-old children. All the model-adjusted mean differences favored the intervention; however, these positive and promising results should be interpreted carefully due to the lack of a cluster-adjusted sample size calculation, the potential lack of power, and the imbalances in sample sizes between clusters and sex proportions within clusters. Considering the exploratory nature of this study and the characteristics of the study design, the effect sizes confidence intervals and intracluster correlation coefficients (ICC) can be used to conduct power analysis and guide the selection of outcomes for larger cluster randomized trials.

4.5.1. Intervention Development

We developed the intervention based on a physical literacy framework (2016) and a conceptual model (2019) proposed by Cairney et al. (6, 7) We also followed the seven steps for implementing an effective preventive training program proposed by Padua et al. (2014) (33). We focused on theoretical- and evidence-based links between the outcomes and accepted clinical events; for example, the connection between the quality of the movement and the risk of musculoskeletal injury, and the understanding of movement competence as a predictor for PA participation and maintenance (21, 27, 41). We strongly considered the affective elements that enhance enjoyment and confidence, and focused on the importance of the environment, context, and feedback when developing and mastering movement skills (6). Based on the evidence reported by Padua et al. (2014) we completed the following steps to implement our intervention: (a) we established administrative support by presenting the study and obtaining approval from the staff at the schools; (b) we created an interdisciplinary team conformed by the investigators (i.e., exercise physiologist, athletic therapist, physiotherapist), PE teachers, staff, and volunteers; (c) we developed a theory-based intervention using links between theoretical constructs and intervention content; (d) we trained the facilitators; (e) we controlled for fidelity; (f) we planned an exit strategy (33). Additionally, we used this study to identify barriers and solutions for a future larger trial. Some barriers include the lack of proper training and logistics as reported by the facilitators. All these elements led to promising results and feasibility evidence that can help improve and support the implementation of our neuromuscular warm up.

4.5.2. Effects of the Intervention

The affective and cognitive elements of our neuromuscular warm-up seem to be effective to positively affect physical literacy constructs, especially the cognitive domain, and the process of movement (6). The feedback and external focused cues may had a moderator effect in the participants' performance. Steffen et al. (2013) suggested that proper feedback and high adherence are crucial elements in effectively facilitating neuromuscular training, regardless of the length of the intervention (40). In our study, many variables may have been directly influenced by feedback and cueing; for example, the movement skills in the ChildFIRST. The ChildFIRST is a process-based assessment tool that focuses on body position, joint angles, and posture (21). The efficacy of neuromuscular training in improving landing mechanics as assessed by the ChildFIRST may stem from core and hip exercises, as well as the feedback provided for correcting lower limb and trunk alignment, which can lead to musculoskeletal injury risk reduction (22).

The results we observed for neuromuscular performance (e.g., vertical jump, horizontal jump, running, and dynamic balance) are similar to those observed through meta-analysis that studied the effects of MIPP and neuromuscular training in similar populations in sports settings (22, 37). Our reported effect sizes are valuable because we observed them in a school setting, in a Hispanic population, which contribute to the enlargement and diversity of future meta-analyses. Our findings related to neuromuscular performance can be explained by specific physiological and neuromuscular mechanisms. In brief, the performance of power based movements, such as vertical jump, horizontal jump, and running has been previously explained by any adaptations in muscles' contractile elements, and neuromuscular activation and coordination, and tendon stiffness (22). Dynamic balance may benefit from enhanced control of shifts in center of gravity and refined automatic postural response patterns (17).

4.5.3. Feasibility

We recruited six more groups (50%) than expected and collected data from 89.6% at baseline and follow up. Adherence (90.1%) and enjoyment (90.1%, mean = 4.36 ± 0.76) feasibility criteria were also met. Compliance (87.8%), fidelity (86.6%), and follow up (89.6%) were slightly below the *a priori* defined thresholds (90%). The facilitators reported that training, logistics, time, and the participants' and facilitators' characteristics should be considered when implementing the intervention as intended. Meeting the criterion for adherence and the higher value for compliance is important as both are influenced by various factors, including the children's beliefs and attitudes towards the intervention, their physical and emotional health, and the support and resources available to them (33). The mean RPE (3.36 ± 1.19) was below the threshold (5), which was set considering that the warm-up should not be very intense activity as its objective is to prepare participants for a more demanding activity (16, 22). Moreover, if the warm-up is very intense, it may affect its compliance and enjoyment (22). Considering that compliance, fidelity and follow up were slightly below the predefined threshold, conducting a larger intervention addressing the reported problems and using proper sampling and randomization is feasible and promising as indicated by the preliminary effectiveness evidence.

4.5.4. Limitations

This study has some limitations. We did not perform a power analysis to calculate the sample size. However, we recruited participants from 18 groups (50% more than planned) composed of 363 participants (20.2 participants per group in average). We also controlled for clustering using GLMMs. Until more robust sampling methods and randomization are used, we cannot know if the participants of the intervention will receive benefit compared to a control group. However, testing the effects of the intervention in a large trial based on our promising findings is the next step. Considering the large sample size, detecting trivial effects as significant was a concern that we tried to mitigate by using a 0.001 significance level. The clusters were unbalanced in sample size and sex proportions; however, we used GLMMs to address the cluster imbalances. Although we randomized the groups to either INT or CON conditions, they were drawn from only two schools (INT = 179 participants, CON = 184 participants), which may compromise the generalization of the results. Moreover, the feedback, descriptions, and instructions were culturally adapted to Hispanic children; thus, future implementations in other settings/latitudes will need to revise the language. Nevertheless, considering the objectives of our study, having 363 participants, 18 groups, and block-randomization of the intervention and control groups favored the feasibility testing and provided preliminary effectiveness evidence in Hispanic participants.

4.6. Conclusions

Our findings provided evidence for the feasibility of a neuromuscular warm-up based on physical literacy and injury prevention strategies. Although recruitment, adherence, enjoyment, and RPE met the *a priori* defined goals, the intervention should be slightly modified to improve compliance, fidelity, and follow up. We also observed preliminary positive evidence on the effectiveness of the proposed warm-up on physical literacy constructs, neuromuscular performance, and musculoskeletal injury risk profile. Due to sampling-related limitations and the characteristics of the experimental design, the results, although promising, should be carefully interpreted; however, the effect sizes and ICCs are useful to conduct power analyses for future interventions.

This feasibility study proposed a novel approach to promote safe PA by connecting physical literary and injury prevention strategies. Physical literacy constructs may enhance engagement and compliance though increased motivation and confidence. Injury prevention strategies may reduce lower-limb musculoskeletal injury risk, which is implicit in physical literacy interventions, PA, PE classes, and sports.

Conflicts of Interest Statement

The authors declare that there are no conflicts of interest.

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Chapter Five: General Discussion

This dissertation explores the connection between the physical literacy model and injury prevention strategies through the assessment and intervention of movement skills. Our overarching goals were: (1) to develop and implement a neuromuscular warm-up based on the physical literacy model and injury prevention strategies for 8-12-year-old children; and (2) to validate the ChildFIRST to assess movement skills in 8-12-year-old children. The specific objectives of this dissertation were: (1) to synthesize the evidence on the effects of MIPP on fundamental movement skills; (2) to test the concurrent and convergent validity of the ChildFIRST; (3) to test the feasibility of a neuromuscular warm-up; and (4) to explore the effects of the neuromuscular warm-up in 8-12-year-old children. Chapter two addresses the first objective of this dissertation through a systematic review and meta-analyses of the effect of MIPP in children and adolescents' fundamental movement skills.[44] Chapter three addresses the second objective by testing the concurrent and convergent validity of the ChildFIRST. Chapter four addresses the third and fourth objectives by testing the feasibility of the neuromuscular warm-up and its effects on the affective and cognitive domains of the physical literacy model, neuromuscular performance, movement competence, and injury risk profile in 8-12-year-old children.

5.1. Chapter Two: Characteristics and Effects of Multicomponent Injury Prevention Programs (MIPP)

Chapter two is a systematic review with meta-analysis of randomized controlled trials published in the *American Journal of Health Promotion*.[44] This chapter established the theoretical foundation for the development and implementation of a neuromuscular warm-up based on movement skills within a framework that combined the physical literacy model and

MIPP. Considering the preventive effects of MIPP,[43] our objective was to understand their specific effects in fundamental movement skills, which are relevant for the physical literacy model, motor development, and injury prevention strategies.[3,7,19,24] We described the characteristics of MIPP (e.g., length, content, dose-response, delivery, timing) to develop the neuromuscular warm-up based on the most relevant evidence.

We observed a combination of statistically- and non-statistically-significant effects on targeted outcomes. We conducted and reported six meta-analyses. Vertical jump ($g=0.39$; $p<0.001$), running speed ($g=0.46$; $p=0.024$), running acceleration ($g=0.65$; $p=0.028$), and dynamic balance ($g=0.23$; $p=0.004$) presented of positive-statistically-significant pooled effects.[44] Horizontal jump ($g=-0.04$; $p=0.724$) and dribbling ($g=0.25$; $p=0.345$) presented non-significant pooled effects.[44] We summarized and reported the characteristics of MIPP, which agreed with other reviews conducted in the injury prevention field with the same population.[43,47–49] All MIPP included at least three components, with strength, plyometrics, and balance being the most used.[33] The majority of MIPP consisted of 2-3 sessions per week, lasting 11-20 minutes, during 6-10 weeks. Twenty-five of the 27 included articles used MIPP as a warm-up due to its potential to induce acute neuromuscular adaptations that help reduce the risk of suffering musculoskeletal injuries during more intense activities.[45,50,51]

The findings of this study led to the definition of a series of criteria to test the feasibility of our neuromuscular warm-up. We identified that adherence, compliance, acceptability (i.e., enjoyment and perceived exertion), and fidelity can affect the effectiveness of MIPP.[52–54] Participants who displayed higher adherence and compliance levels tended to achieve greater gains in biomechanical outcomes, neuromuscular performance, and the reduction of musculoskeletal injury rates.[51,55,56] Various factors can negatively affect acceptability, adherence, and compliance; for instance, MIPP that use repetitive exercises can induce monotony among the participants, which could reduce acceptability and impact their willingness to adhere and comply with them.[57] Moreover, the implementation of MIPP can be compromised if stakeholders hesitate to use them, as MIPP may consume significant time from the practice session.[54] Short MIPP, such as warm-ups, are highly desired due to their acute benefits while requiring minimal time from stakeholders.[51,58]

Unsuccessful MIPP provided important insights for the development of our neuromuscular warm-up. Some of the included studies that implemented MIPP with varying training volumes, intensities, progressions, and contents could not induce positive effects.[52–55] Those studies may have failed to achieve their goals due to specificity issues.[59] MIPP that emphasized on sagittal plane and double-legged movements may hinder biomechanical adaptations in single-legged and/or frontal plane movements.[53] Furthermore, a series of studies reported that MIPP that did not include horizontal jumps may have compromised horizontal jump performance, which was reflected in our meta-analysis ($g=-0.04$; $p=0.724$).[60–62] The focus and use of feedback could also affect the effectiveness of MIPP.[33] For instance, MIPP that focused on providing feedback on technique to reduce landing forces may fail to enhance jump performance.[54] Conversely, Steffen et al. (2008) reported that MIPP led to enhanced leg power, but inadequate technique could account for the lack of improvement in jumping performance, suggesting the necessity for additional feedback.[52] Based on the aforementioned evidence, we developed a neuromuscular warm-up designed to be specific by using active feedback and appropriate attentional cues to improve movement skills (i.e., single- and double-legged) in both the sagittal and frontal planes.

Considering the negative impact that non-adherence, non-compliance, low acceptability, and poor fidelity can have on MIPP,[33,58] we identified potential solutions to inform the development of our neuromuscular warm-up. The proposed solutions align with the physical literacy framework outlined by Cairney et al. (2016), who emphasized that movement-based interventions for children should prioritize enjoyment by fostering a positive interaction with the environment and peers.[13] Incorporating group activities and short sessions can improve acceptability and compliance, confirming the suitability of MIPP in the form of warm-ups.[50] Using progressive exercises can enhance enjoyment and acceptability;[50] additionally, early introduction to MIPP may familiarize youth to exercise-based routines, resulting in improved adherence and long-term compliance.[51,63] Ensuring administrative support from stakeholders within organizations can positively affect implementation fidelity and sustainability of MIPP as suggested by Padua et al. (2014).[58] Showcasing the reduction of musculoskeletal injury rates and the improvements in biomechanics and neuromuscular performance of fundamental movement skills can provide immediate gratification to stakeholder and further enhance acceptability and compliance.[51] Controlling for fidelity during the implementation of MIPP is necessary to determine whether the observed effects are caused by a dose-response relationship.[64]

5.2. Chapter Three: Validity of the Child Focused Injury Risk Screening Tool (ChildFIRST)

Chapter three is a validation study to test the concurrent and convergent validity of the ChildFIRST. This study is under review in *Measurement of Physical Education and Exercise Science.* We developed the ChildFIRST at the Athletic Therapy Research Laboratory at Concordia University with the aim to identify 8-12-year-old children who present poor movement competence and increased risk of lower limb musculoskeletal injury.[24,44,46] We set the theoretical foundation of the ChildFIRST based on an hypothetical relationship between the physical literacy model and injury prevention strategies through the assessment of fundamental movement skills.[24] We established the face and content validity of the ChildFIRST using a modified Delphi process with an international expert panel.[45] We provided inter- and intra-rater reliability evidence for the ChildFIRST using videos that were assessed by 3rd and 4th year college students.[24] Hulteen et al. (2020) published a comprehensive systematic review of the validity and reliability of movement competence assessment tools.[21] In their review, Hulteen et al. reported 107 studies that used several movement competence assessment tools; however no study targeted or incorporated an assessment tool with an injury prevention approach.[21] We validated the ChildFIRST to assess the effects of the neuromuscular warm-up in children's movement competence and injury risk profile. However, the ChildFIRST, as a process-based tool, should be used in conjunction with product-based tools (e.g., vertical jump, horizontal jump, running, dynamic balance) to guarantee a comprehensive assessment.[20]

Since the ChildFIRST approach is unique, we used different instruments to tests its concurrent and convergent validity. We used peak joint angles obtained through 3D motion analysis to test the concurrent validity of ChildFIRST evaluation criteria (n = 18). The analyzed evaluation criteria were related to lower-limb alignment in the frontal and sagittal planes, which determines individual's movement competence and injury risk profile.[65] Although the correlation values were not consistently good for the hips, the evaluation criteria are sensitive enough to properly detect abnormal knee motion and alignment. The results of this study allowed us to target the feedback and instructional cues for the neuromuscular warm-up in chapter 4. Considering that the ChildFIRST allows for a limited observation time, we focused our feedback and provided external focused cues on noticeable movement patterns in the hips and knees. We tested the concurrent validity of the ChildFIRST using the TGMD-3 and the mSEBT, which are commonly used instruments.[66,67] However, these instruments have certain limitations that the ChildFIRST attempts to address.[44] We used three movement skills from the TGMD-3 (e.g., running, single-leg hop, horizontal jump) to test the convergent validity of the same movement skills in the ChildFIRST. The TGMD-3 is a popular valid and reliable process-based assessment tool; however, it assesses motor development and does not directly consider musculoskeletal injury risk in its evaluation criteria.[67] We tested the convergent validity of the dynamic balance movement skills in the ChildFIRST using the mSEBT (i.e., anterior, posteromedial, and posterolateral directions). The mSEBT is also valid and reliable, but it is time consuming, and its instructions may be difficult to accomplish by 8-12-year-old children.[66] We observed positive correlation coefficients between specific movement skills in the ChildFIRST and the TGMD-3 (horizontal jump $r = 0.74$; running $r = 0.71$; single-leg hop $r = 0.66$) and the normalized mSEBT composite scores for each leg (right leg $r = 0.83$, left leg $r = 0.87$). Our findings suggest that the ChildFIRST concurrent and convergent validity evidence that make it an appropriate instrument to evaluate the effects of the neuromuscular warm-up.

The ChildFIRST can be used in groups of up to 40 children and is suitable in different contexts. Although the ChildFIRST only considers the physical factor of the physical literacy model, its injury prevention approach benefits the promotion of safe PA.[44] Considering that the neuromuscular warm-up aims to be used in physical literacy interventions, sport practices, and PE classes, the ChildFIRST can be used to understand children's movement capacities and needs.[45] Establishing the validity of the ChildFIRST may lead to physically literate individuals, lower musculoskeletal injury rates, and increased neuromuscular performance.[45] The ChildFIRST may help improve the adoption of, and compliance with, the neuromuscular training by assessing noticeable changes in movement patterns. The information gained from the ChildFIRST can help effectively inform any positive changes to stakeholders, which is essential to enhance acceptability and compliance.[58]

5.3. Chapter Four: Feasibility and Effects of the Neuromuscular Warm-up

Chapter four is a cluster non-randomized controlled trial that tested the feasibility and outcomes of the neuromuscular warm-up. We defined the *a priori* feasibility criteria based on the results from chapter two.[44] We met the following feasibility criteria: recruitment process (150%), adherence (90.1%), enjoyment (90.1%), and rate of perceived exertion (RPE) (3.36). In contrast, compliance (87.8%), fidelity (86.6%), and the follow up (89.6%) were slightly below the predefined threshold (90%). The assessment protocol, including the ChildFIRST, was feasible in terms of time, enjoyment, and intensity. We included the assessment of neuromuscular performance (i.e., vertical jump, horizontal jump, 20m spring, and dynamic balance) to completement the ChildFIRST and obtain process- and product-based assessment of movement competence as recommended by Logan et al. (2017).[20] Furthermore, we assessed the affective and cognitive domains of the physical literacy model using the CAPL2 to holistically assess the effectiveness of the neuromuscular warm-up.[13,16]

The feasibility criteria, as essential factors for any movement-related intervention, should be seriously considered to understand the potential effects of our neuromuscular warm-up.[56,68,69] We observed that our warm-up was well accepted by the participants as indicated by enjoyment scores. We targeted acceptability by ensuring its appropriateness through the use of movement skills that should be already acquired by 8-12-year-children.[19] Given that children in this age range have different interests compared to adults and older children, we developed the neuromuscular warm-up considering the affective elements that enhance their enjoyment and confidence.[13,14] We also focused on the importance of the environment, context, and feedback when implementing the neuromuscular warm-up to enhance adherence and compliance.[13] We strove to engage stakeholders with the intervention using its potential effectiveness to favor the recruitment process.[68]

The facilitators reported the reasons that compromised fidelity in 44.6% of the sessions. Fidelity refers to the degree to which an intervention is implemented as intended in terms of type, frequency, intensity, and duration.[64] The reported reasons were related to the children's characteristics (24.1%), the training received (17.2%), the session time (13.8%), the logistics (27.6%), and human mistakes (17.2%). These reasons should be accounted in future studies by ensuring that the intervention is delivered by qualified and training facilitators and that all materials are fully available.[68] Various sessions were over the planned time (15 min); however, the average time was 15.6 ± 0.7 min, which was not far from the threshold and was suitable for a warm-up.

Another key aspect of this feasibility study was evaluating the potential effectiveness of the neuromuscular warm-up.[70] Although there are limitations in chapter four, the neuromuscular warm-up had promising effects. Moreover, the effect sizes, confidence intervals, and ICC can be used to conduct power analysis and guide the selection of outcomes for a larger study. Evaluating the effects of the neuromuscular warm-up on the affective and cognitive elements the physical literacy model allowed us to account for the holistic concept of physical literacy as recommended in the literature.[13] The use of the feedback and external focused cues was based on both chapters two and three and may had a moderator effect in the participants' performance. For instance, the ChildFIRST as a process-based assessment tool can detect the effects of proper feedback and cuing as it focuses on body position, joint angles, and posture.[45] The neuromuscular warm-up shares features with other standardized MIPP (i.e., FIFA 11+, Harmoknee) and its effects in neuromuscular performance were similar.[71,72] However, we used a physical literacy approach that differentiates our intervention from the rest of available warm-ups. Given the preliminary effectiveness evidence, conducting a larger intervention that addresses the reported issues and employs proper sampling and randomization is feasible and promising, despite the minor shortcoming in compliance, fidelity, and follow-up that were slightly below the predefined threshold.

5.4. Limitations

Additional to the reported limitations in chapters two, three, and four, this dissertation had some general limitations. Although the ChildFIRST is valid, it is difficult to properly interpret its composite score. A higher ChildFIRST score can be associated with better movement competence and a lower risk of musculoskeletal injury. However, a threshold or a sub score that indicates what construct (i.e., movement competence, musculoskeletal injury risk) is more problematic to the child does not yet exist. We tested the concurrent and convergent validity of the ChildFIRST, but the evidence is limited to 18 out of 40 evaluation criteria for concurrent validity and six movement skills for convergent validity.

The feasibility results cannot be fully generalizable in North America due to sociocultural differences. For instance, Colombian children do not play hockey, which is not a popular sport in South America, and their dynamic balance may differ compared to Canadian Children. Furthermore, is not unusual that public schools in Colombia hire PE teachers only after grade 5th, which may place Colombian children in disadvantage in terms of motor development compared to American or Canadian Children. Our findings in Hispanic children enhance the diversity in the field; for instance, effect sizes can be included in meta-analyses and power analyses for other studies.

We translated all documents and instruments to Spanish when they were available only in English, but we did not validate those translations. The lead researcher, whose native language is Spanish, translated and did-reverse translation of all the material without changing any content of it. In chapter three and four, the statistical analyses may be underpowered mostly due to the multiple comparisons. We tried to mitigate this problem by using appropriate statistical tests while adjusting the significance level.

5.5. Recommendations for Future Research

This dissertation presented a novel neuromuscular warm-up and validity evidence for the ChildFIRST. Our objective was to connect the physical literacy model and injury prevention strategies to propose an original alternative to promote safe PA. Our studies and findings lay the groundwork for future research in the following areas:

1. Improve the neuromuscular warm-up based on the feasibility criteria and facilitator's reports. Developing strategies to enhance the feasibility criteria would increase the likelihood of observing positive effects when implementing the neuromuscular warm-up.
2. Implement the neuromuscular warm-up using a cluster randomized controlled trial. A larger sample with adequate sampling and allocation methods will improve our confidence in the results.
3. Implement the neuromuscular warm-up in different populations to identify sociocultural differences that can affect movement competence and injury risk profile.
4. Study if different types and levels of feedback have a moderator effect on the neuromuscular warm-up effectiveness.

5. Refine the ChildFIRST by considering extra evaluation criteria or a different scoring system. An extra evaluation criterion may increase the ChildFIRST ability to detect movement patterns that may compromise movement competence and musculoskeletal injury risk profile. Using a different scoring system (e.g., 5- or 7-point scales) for the ChildFIRST might better reflect the inherent variability of human movement.
6. Establish the normative data for the ChildFIRST in different populations. The normative data can unleash the potential of the ChildFIRST by providing a meaning to the composite score. The use of sub scales (e.g., injury risk and movement competence sub scales) can also be explored to better differentiate the constructs that need more attention.
7. Establish the construct validity of the ChildFIRST using confirmatory factor analysis.

5.6. Conclusions

Implementing MIPP outside sport-related contexts such as physical literacy interventions, PE classes, and organized PA, can help promote safe PA. MIPP can mitigate musculoskeletal injury risk and positively affect neuromuscular performance in fundamental movement skills.

The ChildFIRST has now face, content, concurrent, and convergent validity evidence. Implementing an injury prevention approach to traditional movement competence assessment as intended by the ChildFIRST may help promote safe PA by identifying individuals with poor movement competence and higher risk of musculoskeletal injury. The ChildFIRST concurrent validity relates to the evaluation criteria associated with lower-limb musculoskeletal injury risk, and its convergent validity relates to horizontal jump, running, single-leg hop, sideways hop and hold, two-to-one foot hop and hold, and 90-degree jump and hold.

A novel neuromuscular warm-up showed promising effects on physical literacy constructs, neuromuscular training, and injury risk profiles in 8-12-year-old children. We observed positive model-adjusted mean differences on affective, cognitive, and physical domains of the physical literacy model. We also observed positive model-adjusted mean differences in neuromuscular performance for vertical jump, horizontal jump, 20m sprint, and dynamic balance. A plan to enhance compliance, fidelity, and follow up is needed before implementing the neuromuscular warm-up in a larger study. Probabilistic sampling methods and proper randomization and allocation are necessary to fully understand the causal effects of our neuromuscular warm-up.

We a proposed novel approach to promote safe PA by connecting physical literary and injury prevention strategies using a neuromuscular warm-up. Physical literacy constructs may enhance engagement and compliance though increased motivation and confidence. Injury prevention strategies may reduce lower-limb musculoskeletal injury risk, which is implicit in physical literacy interventions, PA, PE classes, and sports. Our neuromuscular warm-up has the potential to positively affect 8-12-year-old children's physical literacy constructs, neuromuscular performance, and injury risk profile, which supports its implementation in multiple PA-related contexts to contribute to the promotion of safe PA.

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Note: These references are for chapters one and five. The references for chapters two, three, and four can be found at the end of each chapter to keep the integrity of the published/submitted versions.

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Appendices

Appendices for Chapter Two: Effects of Multicomponent Injury Prevention Programs on Children and Adolescents' Fundamental Movement Skills: A Systematic Review with Meta-Analyses

Appendix A. Search Strategy

Table A1. Search Strategy.

Database	Search Strategy/Phrase
PubMed	(((child[Title/Abstract] OR children[Title/Abstract] OR kid[Title/Abstract] OR kids[Title/Abstract]) OR child[MeSH Major Topic]) OR ((adolescent[Title/Abstract] OR adolescents[Title/Abstract]) OR adolescent[MeSH Major Topic]) OR ((youth[Title/Abstract] OR young[Title/Abstract]) OR youth sports[MeSH Major Topic])) AND (((injury[Title/Abstract] OR injuries[Title/Abstract]) OR athletic injuries[MeSH Major Topic]) AND (prevention[Title/Abstract] OR preventative[Title/Abstract]) OR (program[Title/Abstract] OR programs[Title/Abstract] OR programme[Title/Abstract] OR programmes[Title/Abstract]) OR ((warm up[Title/Abstract] OR warm-up[Title/Abstract]) OR warm up exercise[MeSH Major Topic]) OR (neuromuscular[Title/Abstract] OR neuromuscular training[Title/Abstract] OR integrative neuromuscular training[Title/Abstract])) AND ((athletic performance[MeSH Major Topic]) OR ((balance[Title/Abstract] OR dynamic balance[Title/Abstract] OR static balance[Title/Abstract] OR stability[Title/Abstract]) OR postural balance[MeSH Major Topic]) OR ((biomechanic[Title/Abstract] OR biomechanics[Title/Abstract] OR biomechanical[Title/Abstract]) OR biomechanical phenomena[Mesh:noexp]) OR (jump OR jumps OR jumping) OR (hop OR hops OR hopping) OR (land OR lands OR landing) OR ((jog OR jogs OR jogging OR sprint OR sprints OR sprinting OR run OR runs OR running) OR running[MeSH Major Topic]) OR (cutting tasks) OR (lower extremity[MeSH Major Topic]) OR (locomotion[MeSH Major Topic]) OR (motor skill[MeSH Major Topic]))
Scopus	(TITLE-ABS-KEY ((child*) OR (kid*) OR (adolescent*) OR (youth OR young))) AND (TITLE-ABS-KEY ((((injur*) AND (prevent*) AND (program*)) OR ((injur*) AND (prevent*)) OR program*) OR ("warm up" OR warm-up) OR (neuromuscular OR "neuromuscular training" OR "integrative neuromuscular training" OR nmt))) AND (TITLE-ABS-KEY (("athletic performance" OR "neuromuscular performance" OR performance) OR (balance OR "dynamic balance" OR "static balance" OR stability OR "postural balance") OR (biomechanic* OR kinetic* OR kinematic*))) AND (TITLE-ABS-KEY ((jump*) OR (land*) OR (run*) OR (hop*) OR (cut*) OR (locomot*) OR ("motor skill" OR "movement skill" OR skill*)))
Web of Science	TOPIC: (child* OR kid* OR adolescent* OR youth OR young) AND TOPIC: (((injur* AND prevent*) OR (injur* AND prevent* AND program*) OR program*) OR ("warm up" OR warm-up) OR (neuromuscular OR "neuromuscular training" OR "integrative neuromuscular training" OR NMT)) AND TOPIC: (("athletic performance" OR "neuromuscular performance" OR performance) OR (balance OR "dynamic balance" OR "static balance" OR stability OR "postural balance") OR (biomechanic* OR kinetic* OR kinematic*)) AND TOPIC: (jump* OR land* OR run* OR hop* OR cut* OR locomot* OR ("motor skill" OR "movement skill" OR skill*))

SPORTSDiscus	(child* OR kid* OR adolescent* OR youth OR young) AND (((injur* AND prevent* AND program*) OR (injur* AND prevent*) OR program*) OR ("warm up" OR warm-up) OR (neuromuscular OR "neuromuscular training" OR "integrative neuromuscular training" OR NMT)) AND (("athletic performance" OR "neuromuscular performance" OR performance) OR (balance OR "dynamic balance" OR "static balance" OR stability OR "postural balance") OR (biomechanic* OR kinetic* OR kinematic*)) AND (jump* OR land* OR run* OR hop* OR cut* OR locomot* OR ("motor skill" OR "movement skill" OR skill*))

Appendix B. Risk of bias Assessment

Table B1. Physiotherapy Evidence Database (PEDro) scores.

Study	Eligibility Criteria Specified+	Random Allocation	Concealed Allocation	Baseline Comparability	Blinded Subjects	Blinded Therapists	Blinded Assessors	Adequate Follow-Up	Intention-to-Treat Analysis	Between Group Comparisons	Point Estimates and Variability	Total Score
Kilding et al., 2008	0	1	0	1	0	0	0	1	1	1	1	6/10
Steffen et al., 2008	1	1	0	1	0	0	0	1	1	1	1	6/10
Lim et al., 2009	0	1	0	1	0	0	0	1	1	1	1	6/10
DiStefano et al., 2010	1	1	0	1	0	0	0	1	1	1	1	6/10
Vescovi & VanHeest, 2010	1	1	0	1	0	0	0	0	1	1	1	5/10
Reis et al., 2013	0	1	0	0	0	0	0	1	1	1	1	5/10
Brown et al., 2014	1	1	0	1	0	0	0	0	1	1	1	5/10
Zech et al., 2014	1	1	1	1	0	0	0	1	1	1	1	7/10
Root et al., 2015	1	1	0	1	1	1	1	1	0	1	1	8/10
Rössler et al., 2016	1	1	1	1	0	0	0	1	1	1	1	7/10
Ayala et al., 2017	1	1	1	1	0	0	1	0	1	1	1	7/10
Ondra et al., 2017	1	1	0	1	0	0	0	1	1	1	1	6/10
Akbari et al., 2018 and 2019	1	1	0	1	0	0	0	1	1	1	1	6/10
De Ste. Croix et al., 2018	0	1	1	1	0	0	0	1	1	1	1	7/10
Gatterer et al., 2018	0	1	0	1	0	0	0	1	1	1	1	6/10
Pomares-Noguera et al., 2018	1	1	1	1	0	0	0	1	1	1	1	7/10
Taylor et al., 2018	1	1	1	1	0	0	0	1	1	1	1	7/10
Zarei et al., 2018	0	1	0	1	0	0	0	0	1	1	1	5/10
Zarei et al., 2018	1	1	0	1	0	0	0	0	1	1	0	4/10
McKenzie et al., 2019	0	1	0	1	0	0	0	0	1	1	1	5/10
Pardos-Mainier et al., 2019	0	1	0	0	0	0	0	1	1	1	1	5/10
Parsons et al., 2019	1	1	0	1	0	0	1	1	1	1	1	7/10
Trajkovic & Bogataj, 2020	1	1	0	1	0	0	0	1	1	1	1	6/10

Forrest et al., 2020	1	1	1	1	0	0	0	1	1	1	1	7/10
Font-Lladó et al., 2020	1	1	0	1	0	0	1	1	0	1	1	6/10
Teixeira et al., 2021	1	1	0	1	1	0	0	0	0	1	1	5/10

⁺ Not included in the total score.

Appendix C. Risk of publication bias plots

Figure C1. Funnel plot for vertical jump.

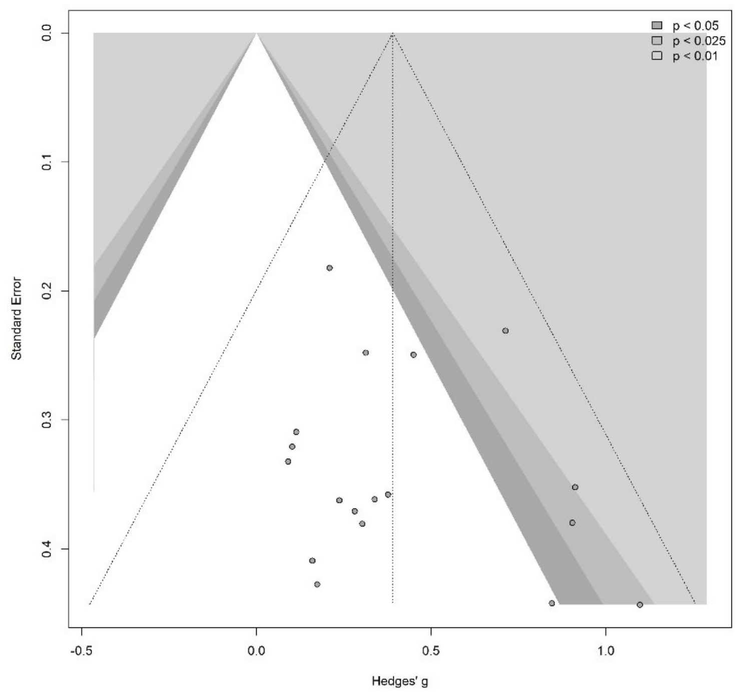


Figure C2. Funnel plot for horizontal jump.

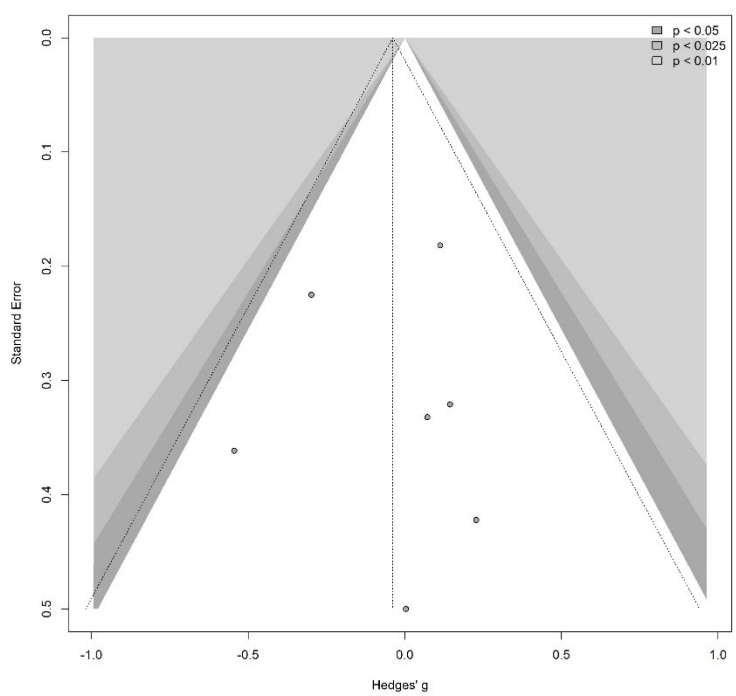


Figure C3. Funnel plot for dynamic balance.

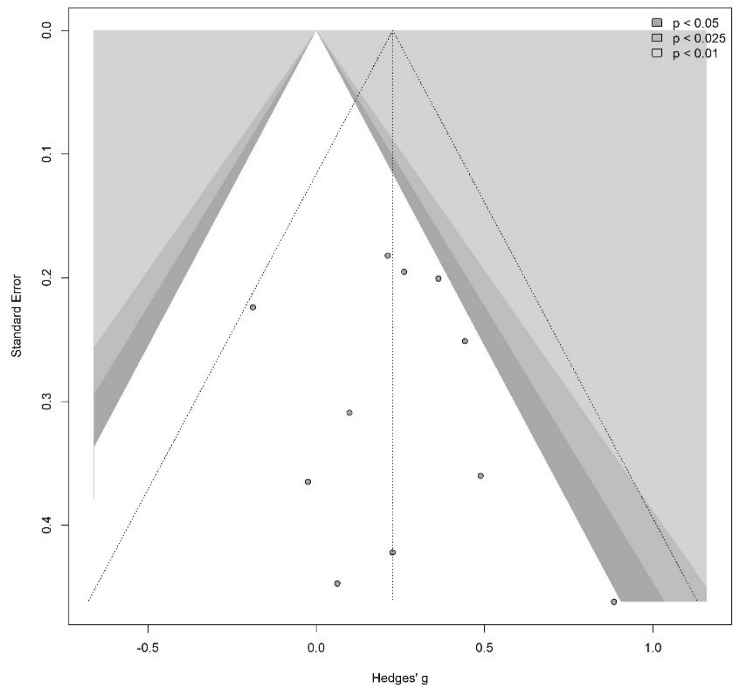


Figure C4. Funnel plot for running speed.

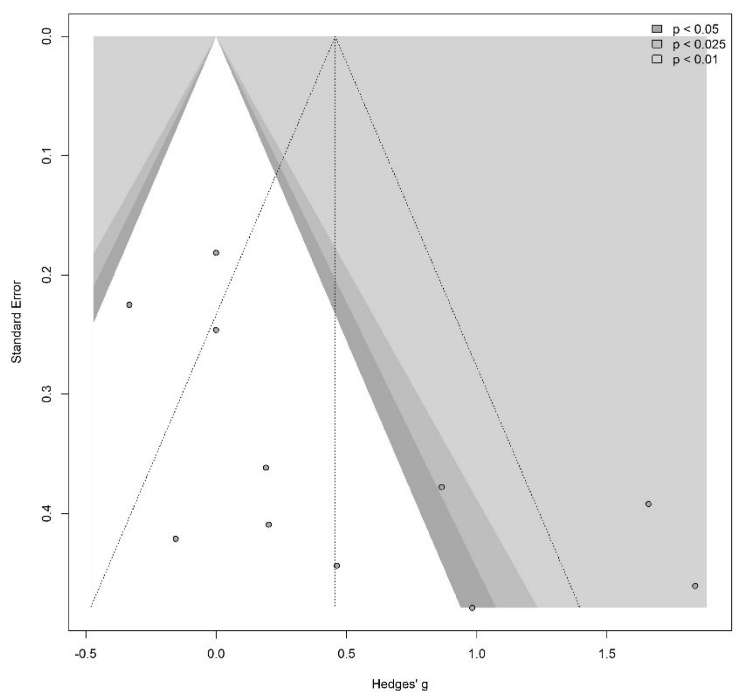


Figure C5. Funnel plot for running acceleration.

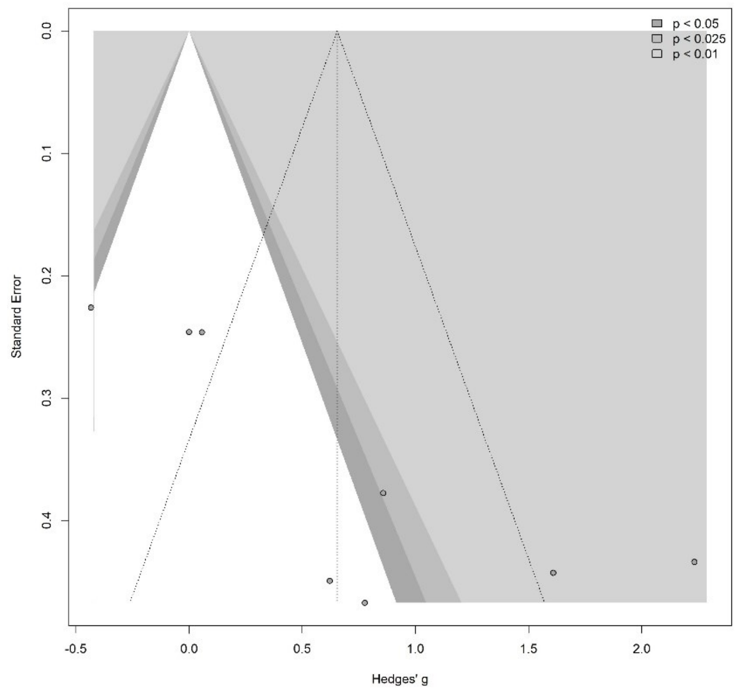
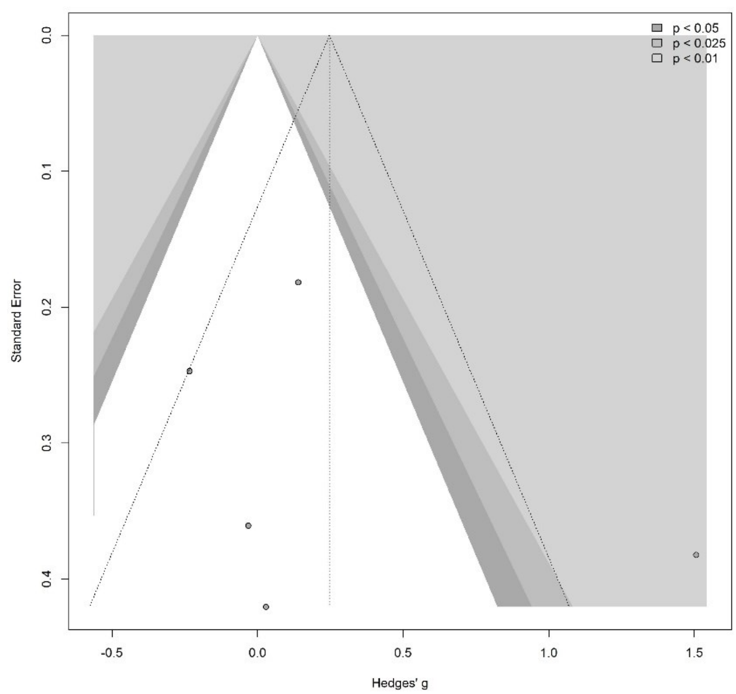


Figure C6. Funnel plot for dribbling.



Appendices for Chapter Four: Feasibility and Effects of a Neuromuscular Warm-Up based on the Physical Literacy Model and Injury Prevention Strategies for 8-12-Year-Old Children

Appendix 1. Physical-Activity-Related Messages

Session	Message
1	Physical activity means moving our bodies in different ways, like running, jumping, throwing, catching, and doing other fun exercises.
2	Sedentarism means we are not moving and sitting or lying down for a long time, like doing homework, watching TV, or playing video games.
3	We need to move our bodies for at least 60 minutes each day! We can run, jump, and do other fun exercises to stay healthy.
4	Cardiovascular endurance means our heart is working well to pump blood to all our muscles!
5	Muscular strength is the capacity of our muscles to push, pull, and move things, including our body.
6	Warming up our bodies will help us prepare for our physical education class or sports practice.
7	Stretching at the end of our activity is important to help our bodies cool down.
8	If you want to get better at a movement, you must practice it and do it right with the help of an adult!

Appendix 2. CONSORT Diagram.