INTER-LIMB ASYMMETRIES IN FUNCTIONAL PERFORMANCE AND NON-CONTACT LOWER-LIMB INJURY IN PEDIATRIC-AGE ATHLETES

by

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Abstract

Background: Previous findings regarding the association between inter-limb asymmetries in functional performance and lower-limb injury in sports are highly inconsistent, and few studies have focused on pediatric-age athletes.

Purpose: To comprehensively examine inter-limb asymmetries in lower-limb functional performance and their association with non-contact lower-limb injury in pediatric-age athletes.

Methods: A narrative (Chapter 2) and systematic (Chapter 3) review were composed to provide background and identify gaps. A retrospective survey was conducted to compare injury risk in laterally vs. non-laterally dominant sport in 6-17 y athletes (Chapter 4). Inter-limb asymmetry in lower-limb functional performance was assessed for 9-11 y fencers and taekwondo athletes to examine the asymmetry profile in child athletes specialized in laterally vs. non-laterally dominant sport (Chapter 5). To explore whether inter-limb asymmetry can predict injury, 456 taekwondo athletes (6-17 y) were assessed for asymmetries in unilateral jumps and Star Excursion Balance Test (SEBT), and then prospectively traced for injury for 12 months (Chapter 6). Lastly, inter-limb asymmetry in lower-limb functional performance was assessed for 9-11 y taekwondo athletes at the rested and fatigued state to explore the effects of fatigue on asymmetry (Chapter 7).

Results: Greater risk of non-contact lower-limb injury was shown in athletes specialized in laterally vs. non-laterally dominant sports (Chapter 4). Inter-limb asymmetries were demonstrated in both laterally and non-laterally dominant sport, with a limb by sex interaction (Chapter 5). The increase in inter-limb asymmetry in single-leg countermovement jump height indicates greater risk of non-contact lower-limb injury in both sexes, while the increase of inter-limb asymmetry in hop and triple-hop distance indicates greater risk of non-contact lower-limb

injury only in boys (Chapter 6). Inter-limb asymmetry in triple-hop distance increased with fatigue; inter-limb asymmetry in anterior reach distance in SEBT decreased with fatigue (Chapter 7).

Conclusions: The current findings have important implications for pediatric sport. Inter-limb asymmetries were shown in childhood-age athletes in both laterally and non-laterally dominant sports; the amount of asymmetry can be affected by fatigue. Inter-limb asymmetries in unilateral jumps can be used to evaluate risk of non-contact lower-limb injury in pediatric-age athletes, while there is a difference between sexes.

Lay Summary

The main purpose of this research was to examine bilateral difference (inter-limb asymmetry) in performance of jumps and balance in youth athletes specialized in asymmetrical vs. symmetrical sport, and to investigate whether inter-limb asymmetry can predict sport injury. Additionally, by conducting a survey, the research aimed to identify the effects of lateral dominance in sports (asymmetrical vs. symmetrical sports) on risk of sport injury in youth athletes. The research also aimed to explore the effects of fatigue on bilateral difference in youth athletes.

Few studies have examined the association between inter-limb asymmetry and sport injury based on youth athletes. The profile of inter-limb asymmetry in children specialized in asymmetrical vs. symmetrical sports was also not clear. The findings of this thesis aimed to contribute greater understanding in these areas, which will help guide injury prevention and prediction in youth athletes.

Preface

The designing of the project was initiated by Yanfei Guan. Yanfei Guan conducted and coordinated the recruitment of participants and data collection. All data analyses, statistical analyses, and writing of this thesis were conducted by Yanfei Guan. All studies included in this thesis were evaluated and facilitated by Dr. Darren Warburton, who provided huge support to the author, granting the autonomy that permits the pursuit of research goals. The author's committee including Dr. Shannon Bredin, Dr. Jack Taunton, and Dr. Qinxian Jiang all provided exceptional support, guidance, and valued feedback throughout the investigations. Dr. Yongfeng Li and Dr. Qinxian Jiang provided exceptional guidance and support to the process of data collection in Shandong Province, China. All research conducted in China was under the direction of Drs. Li and Jiang.

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A version of Chapter 7 has been published. Guan Y., Bredin S., Jiang Q., Taunton J., Li Y., Wu N., Wu L., & Warburton D. (2021). The effect of fatigue on asymmetry between lower limbs in functional performances in elite child taekwondo athletes. *Journal of Orthopaedic Surgery and Research*, 16(1): 33. Yanfei Guan was responsible for study design, data collection and analyses, statistical analyses, and manuscript writing. Dr. Shannon Bredin, Dr. Qinxian Jiang, and Dr. Jack Taunton contributed to the study design and critical revision of the manuscript. Dr. Yongfeng Li, Nana Wu, and Lina Wu contributed to data collection, data interpretation, and revision of the manuscript. Dr. Darren Warburton was the senior author of this manuscript and conducted the final review and editing of the article prior to submission.

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Table of Contents

List of Tables

List of Figures

List of Abbreviations

Acronyms

ACL	Anterior cruciate ligament
ANOVA	Analysis of variance
CI	Confidence interval
CMJ	Countermovement jump
EMG	Electromyography
H/Q	Hamstrings/quadriceps
ICC	Intraclass correlation coefficient
OR	Odds ratio
ROC	Receiver Operator Characteristic
SD	Standard deviation
SEBT	Star Excursion Balance Test
U	Under

Abbreviations

cm	centimeter – unit of length measurement
d	day
fps	frames per second
hr	hour
Hz	Hertz
kg	kilogram
m	meter

mo	month
s	second
wk	week
y	year

Glossary

Acute injury	Injuries occurred suddenly during physical activities.
Anthropometric tests	Tests of anthropometry include measurements of body size, structure, and composition.
Dynamic balance	The ability to maintain postural stability when completing a task in a dynamic situation (Hrysomallis, McLaughlin, & Goodman, 2006).
Functional performance	Performance in strength/power, proprioception, flexibility, and neuromuscular coordination/control (Bolgla & Keskula, 1997; McGrath et al., 2016).
Inter-limb asymmetry	The difference (in function, performance, anthropometrics, and biomechanics in sport-specific movement) between the two sides of limbs.
Isokinetic strength	The capacity to produce force or torque with voluntary isokinetic (muscles contract and shorten at a constant speed) contraction. During the isokinetic strength test, the force exerted by the muscle can vary depending on the position of the joint in its range of motion and the effort of the participant.
Isometric strength	The capacity to produce force or torque with a voluntary isometric (muscles maintain a constant length and the affected joint does not move) contraction. No body movement occurs during the isometric strength test.

Lateral dominance	In terms of the lower extremities, lateral dominance refers to the superiority of one side of the leg over the other in performing a specific motor task.
Lateral preference	In terms of the lower extremities, lateral preference is the consistent use of one side of the legs to perform a task.
Laterally dominant sport	In terms of the lower extremities, a sport which requires large amount of movement characterized by the two sides of legs performing/functioning differently is classified as a laterally dominant sport. For example, in lunge which is frequently performed in fencing, tennis, and badminton, the dominant leg performs as the leading leg, and the non-dominant leg performs as the supporting leg (Guan, Guo, Wu, Zhang, & Warburton, 2018).
Modifiable risk factors	Risk factors that can be modified, treated, or controlled through intervention.
Muscle flexibility	The range of motion available to a joint or series of joints (Gleim & McHugh, 1997).
Non-contact lower-limb injury	A medical problem to lower limbs via a non-contact mechanism. Injuries caused by contact with equipment or another player are not included.

Non-laterally dominant sport	In terms of the lower extremities, a sport characterized by the two sides of legs equally involved in movement is classified as a non-laterally dominant sport, such as running, swimming, and cycling. In addition, a sport that requires large amount of single-leg jumps or support/drive on both sides is also classified as a non-laterally dominant sport, despite the fact that the dominant leg is usually more involved than the non-dominant leg in practical action (Grobbelaar, 2003).
Overuse injury	A category of sport-related injuries that result from cumulative trauma or repetitive use and stress (Yang et al., 2012).
Peak height velocity	The period of time in which an adolescent experiences their fastest upward growth in their stature.
Pediatric-age athletes	Athletes aged under 18 y.
Star Excursion Balance Test	Originally developed by Gray (1995), the test offers a simple, reliable, and low-cost method for the assessment of dynamic balance (Olmsted, Carcia, Hertel, & Shultz, 2002). The goal of the test is to obtain the maximum reach distance of the performer along the eight directions using the contralateral limb while maintaining a unilateral stance with solid foundation (Olmsted et al., 2002).
Static balance	The ability to maintain postural stability with a still stance on a firm surface (Hrysomallis et al., 2006).
Time-loss injury	An injury requiring removal from the current or subsequent session of sport training or competition.

Y Balance Test	The Y Balance Test is a simplified version of the Star Excursion Balance Test with three reach directions (anterior, posteromedial, and posterolateral), using a device composed of three pieces of pipes extending in the anterior, posteromedial, and posterolateral directions (Plisky et al., 2009).

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Chapter 1: Introduction

1.1 Executive summary

Inter-limb asymmetry refers to the difference between the two sides of limbs (Bishop, Turner, & Read, 2018; Hodges, Patrick, & Reiser, 2011). Lower-limb functional performance usually refers to the performance in lower-limb strength/power, proprioception, flexibility, and neuromuscular coordination/control (Bolgla & Keskula, 1997; McGrath et al., 2016). Greater asymmetry between lower limbs in functional performance has been associated with increased risk of lower-limb injury in sports (Ford, Myer, & Hewett, 2003; Knapik, Bauman, Jones, Harris, & Vaughan, 1991). Inter-limb asymmetry in lower-limb functional performance has been reported in both laterally dominant (Nyström et al., 1990) and non-laterally dominant sports (Maloney, 2019; Newton et al., 2006; Pappas, Paradisis, & Vagenas, 2015). Laterally dominant sports (e.g., fencing, badminton, tennis) are characterized by the two sides of lower limbs frequently performing in different patterns (Guan et al., 2018). In contrast, non-laterally dominant sports (e.g., running, taekwondo, swimming) are characterized by the two sides of lower limbs equally involved in the performance of the movement, requiring equal mastery of techniques with the dominant and non-dominant leg (Grobbelaar, 2003). There are a number of reasons for the development of inter-limb asymmetry. For example, inter-limb asymmetry may be generated from limb preference (dominant vs. non-dominant limb) in sport (Loffing, Hagemann, Strauss, & MacMahon, 2016); the preference of one limb may cause uneven development of neuromuscular function in long-term training and competition (Loffing et al., 2016). Further, in laterally dominant sports, the laterally dominant moving pattern (e.g., the lunge in fencing and badminton) in long term may lead to more asymmetrical adaptions in lower extremities (Hart et al., 2016). However, there is a lack of research comparing the amount of inter-limb asymmetry between athletes specialized in laterally vs. non-laterally dominant sports, revealing a gap in the literature. Comparing inter-limb asymmetries between studies is also difficult, due to the variety in assessments and ways to calculate asymmetry.

The validity of using inter-limb asymmetry in lower-limb strength/power and dynamic balance (or postural control) to predict lower-limb injury has been widely examined. Research has demonstrated that inter-limb asymmetries in unilateral jump performance significantly predict risk of non-contact lower-limb injury in collegiate athletes (Warren, Lininger, Smith, Copp, & Chimera, 2020). Concerning the dynamic balance, a 4 cm or greater inter-limb asymmetry in posterolateral reach distance in the Y Balance Test indicated greater risk of patellofemoral pain in male military recruits (Nakagawa, dos Santos, Lessi, Petersen, & Silva, 2020). However, there are also a number of studies showing no association between inter-limb asymmetry (in lower-limb strength/power and dynamic balance) and sport injury (Brumitt, Nelson, Duey, Jeppson, & Hammer, 2019; Butler, Lehr, Fink, Kiesel, & Plisky, 2013; Lai et al., 2017; Markovic, Šarabon, Pausic, & Hadžić, 2020). A potential explanation for the discrepancy between findings might be the lack of standardization in methodology and data collection.

Previous studies have involved different types of injuries when examining the effects of inter-limb asymmetry in lower-limb functional performance on risk of lower-limb injury in sport; most studies only included non-contact injuries into analyses, while some studies included both non-contact and contact injuries (Brumitt, Heiderscheit, Manske, Niemuth, & Rauh, 2013; Gonell, Romero, & Soler, 2015; Knapik et al., 1991; Lai et al., 2017; Sieland et al., 2020; Steidl-Muller, Hildebrandt, Muller, Fink, & Raschner, 2018). Non-contact injuries are often caused by intrinsic factors including neuromuscular disorders; however, contact injuries are often caused by contact with the equipment or another athlete in training or competition, and thus associating inter-limb asymmetry with the risk of contact injury may be unsubstantiated (Gonell et al., 2015).

An important limitation in the literature is the paucity of research focusing on pediatric-age athletes. Compared with adults, pediatric-age athletes are more vulnerable to sports-related injuries because of the stage of maturation of growth cartilage and the musculoskeletal system (Cuff, Loud, & O'riordan, 2010; Radelet, Lephart, Rubinstein, & Myers, 2002). According to the available data, inter-limb asymmetries in jump performance (assessed with a single-leg countermovement jump (CMJ)) (Read, Oliver, Croix, Myer, & Lloyd, 2018) and dynamic balance (assessed with the Y Balance Test) (Read et al., 2020) significantly predict non-contact lower-limb injury in pediatric-age male athletes; however, no evidence is available for pediatric-age female athletes. Moreover, few studies have addressed the potential effects of sex (females vs. males) on the relationship between inter-limb asymmetry in lower-limb functional performance and lower-limb injury. Further studies are needed to explore the difference between sexes when using inter-limb asymmetry in lower-limb functional performance to predict non-contact lower-limb injury.

In addition, research has suggested the importance of investigating the effects of fatigue on inter-limb asymmetry in lower-limb functional performance, due to the potential for asymmetry to become more prominent at a fatigued state (Bishop, McCauley, et al., 2019; Bromley et al., 2021; Kons, Orssatto, et al., 2020). For example, the increased inter-limb asymmetry may play a role in the heightened risk of injury during the latter stage of a football (Ekstrand, Hägglund, & Waldén, 2011) and rugby (King, 2006) match. Research has demonstrated that inter-limb asymmetry in unilateral jump performance increased at a fatigued state (Bishop, McCauley, et al., 2019; Bromley et al., 2021; Kons, Orssatto, et al., 2020); however, there is a lack of research examining the effects of fatigue on inter-limb asymmetries in other functional performance such as dynamic balance (or dynamic postural control) and muscle flexibility. Moreover, current literature has mostly examined the effects of fatigue on functional inter-limb asymmetry in adult athletes, while findings generated from pediatric-age athletes are not available.

1.2 Purposes and hypothesis

The purpose of this thesis is to address some of the knowledge gaps related to inter-limb asymmetry in lower-limb functional performance and their effects on risk of non-contact lower-limb injury in pediatric-age athletes. Four empirical studies were conducted as described below.

1.2.1 A survey for risk factors of non-contact lower-limb injury in pediatric-age athletes

The purpose of this study was to examine the effects of lateral dominance in sports (laterally vs. non-laterally dominant sports) on non-contact lower-limb injury, and to identify risk factors of non-contact lower-limb injury in pediatric-age athletes. It was hypothesized that:

1. lateral dominance in sports (laterally vs. non-laterally dominant sports) is a significant risk factor for non-contact lower-limb injury.
2. pediatric-age athletes specialized in laterally dominant sports will sustain greater risk of non-contact lower-limb injury compared to those specialized in non-laterally dominant sports.

1.2.2 Inter-limb asymmetry in children practicing laterally vs. non-laterally dominant sports

The purpose of this study was to examine inter-limb asymmetry in lower-limb functional performance (unilateral jumps and dynamic balance) in children specialized in laterally vs. non-laterally dominant sports. It was hypothesized that:

1. children specialized in laterally dominant and non-dominant sports will show inter-limb asymmetry in lower-limb functional performance.
2. laterally dominant sports will be associated with greater inter-limb asymmetry.

1.2.3 Effects of inter-limb asymmetry on risk of non-contact lower-limb injury – a prospective study in pediatric-age athletes

The purpose of this study was to examine whether inter-limb asymmetries in jump performance and dynamic balance can predict non-contact lower-limb injury in pediatric-age athletes. It was hypothesized that:

1. greater inter-limb asymmetries in jump performance and dynamic balance indicate higher risk of non-contact lower-limb injury in both sexes in pediatric-age athletes.

1.2.4 Effects of fatigue on inter-limb asymmetry in pediatric-age athletes

The purpose of this study was to compare the amount of inter-limb asymmetries in lower-limb functional performance at the rested vs. fatigued state in pediatric-age athletes. It was hypothesized that:

1. the amount of inter-limb asymmetry in each functional test will increase at the fatigued state.

1.3 Overview of thesis

The thesis consists of eight chapters. Chapter 2 includes a narrative review of the literature regarding the assessments, calculation, and contributors of inter-limb asymmetries, and the profile of inter-limb asymmetry in pediatric-age athletes. Chapter 3 provides a systematic review of the literature pertaining to the association between inter-limb asymmetry in lower-limb functional performance and sport injury. Chapter 4 examines the effects of lateral dominance in sports (laterally vs. non-laterally dominant sports) on risk of non-contact lower-limb injury, and risk factors of non-contact lower-limb injury in pediatric-age (6-17 y) athletes with a retrospective survey. Chapter 5 examines the bilateral difference in performance of unilateral jumps and the Star Excursion Balance Test (SEBT) in 9-11 y old fencers vs. taekwondo athletes. Chapter 6 examines the association between inter-limb asymmetry in lower-limb functional performance and non-contact lower-limb injury in pediatric-age (6-17 y) athletes with a prospective design. Chapter 7 examines the effects of exercise-induced fatigue on inter-limb asymmetry in lower-limb functional performance in 9-11 y old athletes. The integration of major findings, strengths and limitations, implications, and directions for future research are presented in Chapter 8.

Chapter 2: Literature Review

This chapter provides an overview on tests used for examining inter-limb asymmetry, ways of calculating inter-limb asymmetry, contributors to inter-limb asymmetry, and the profile of inter-limb asymmetry in pediatric-age athletes. This chapter provides background information for the thesis, and identifies gaps in these areas.

2.1 Defining inter-limb asymmetry

Inter-limb asymmetry (or bilateral asymmetry, bilateral difference) is defined as the difference of one limb with respect to the other (Bishop, Turner, et al., 2018; Hodges et al., 2011). Focusing on lower extremities, inter-limb asymmetry has been widely reported as a percentage of or absolute difference in functional performance between the dominant vs. non-dominant (Eagle et al., 2019; Steinberg et al., 2020), right vs. left (An, Wong, & Cheung, 2015; Gilgen-Ammann, Taube, & Wyss, 2017; Gonell et al., 2015), stronger vs. weaker (Sugiyama et al., 2014; Wong et al., 2007), or injured vs. non-injured (Jordan, Aagaard, & Herzog, 2015; Rohman, Steubs, & Tompkins, 2015) limbs. In this thesis, inter-limb asymmetry will also be discussed under this context.

2.2 Tests examining inter-limb asymmetry

2.2.1 Isometric and isokinetic strength tests

Inter-limb asymmetries in lower-limb strength have been widely examined with isometric and isokinetic strength tests. Inter-limb asymmetry in isometric strength is assessed by measuring the isometric strength of targeted muscles of each side using a hand-held or externally fixed dynamometry (Beshay, Lam, & Murrell, 2011). Similarly, inter-limb asymmetry in isokinetic strength is assessed by measuring the isokinetic strength of targeted muscles of each side using an isokinetic dynamometry (Kozinc, Marković, Hadžić, & Šarabon, 2021). For isometric strength, inter-limb asymmetries in peak force in knee extensors and flexors (Kong & Burns, 2010), peak force in hip adductors (Markovic et al., 2020) and abductors (Brophy et al., 2009), and maximum strength and rate of force development in mid-thigh pulls (Owens et al., 2011) have been examined. For isokinetic strength, inter-limb asymmetries in peak torques of knee flexors and extensors (Eagle et al., 2019; Izovska et al., 2019; Knapik et al., 1991; Kong & Burns, 2010) are most widely reported in the literature.

One advantage of using isometric and isokinetic strength tests is that the hamstrings to quadriceps (H/Q) ratio can be assessed, and thus the inter-limb asymmetry in H/Q ratio can be calculated. Conventionally, the H/Q ratio is determined by the ratio between the peak torque in the hamstrings and quadriceps measured during concentric contraction, while the functional H/Q ratio is determined by the ratio between the peak torque in hamstrings measured during eccentric contraction and the peak torque in quadriceps measured during concentric contraction (Aagaard, Simonsen, Trolle, Bangsbo, & Klausen, 1995; Aagaard, Simonsen, Magnusson, Larsson, & Dyhre-Poulsen, 1998; Pellicer-Chenoll et al., 2017). The commonly accepted H/Q ratio ranges from 50% to 80% under various knee angles and angular velocities (Kong & Burns, 2010). Comparing the H/Q ratio between the involved and uninvolved leg has been used for evaluating progress during rehabilitation in patients with lower-limb injury (Kannus, 1988; Kong & Burns, 2010). Inter-limb asymmetries in isometric and functional isokinetic H/Q ratio have also been examined in injury-free individuals for the purpose of injury prediction (Kong & Burns, 2010; Pellicer-Chenoll et al., 2017).

2.2.2 Jump tests

Single-leg jump tests have been widely used to examine inter-limb asymmetries in lower-limb power; the inter-limb asymmetries in single-leg CMJ height (Bishop, Read, McCubbine, & Turner, 2021; Fort-Vanmeerhaeghe, Gual, Romero-Rodriguez, & Unnitha, 2016; Turner et al., 2016), single-leg hop distance (Sannicandro, Cofano, Rosa, & Piccinno, 2014), and single-leg triple-hop distance (Bampouras & Dewhurst, 2018; Bishop et al., 2021) were commonly reported parameters. In single-leg CMJ, inter-limb asymmetries in kinetic parameters (e.g., peak vertical force, peak power) were also examined (Ceroni, Martin, Delhumeau, & Farpour-Lambert, 2012). In addition, a couple of studies assessed the horizontal distance in single-leg crossover hop (Bishop et al., 2021), side hop (Sannicandro, Cofano, et al., 2014), and 6-m timed hop (Bampouras & Dewhurst, 2018) to determine asymmetries between the two sides.

Most assessments using single-leg jump tests can be time-efficient and low-cost. In single-leg hops, the goal is to obtain the maximum horizontal distance of a hop or several consecutive hops using one leg. The horizontal hop distance from the starting line to the participant's final landing heel can be assessed using a tape measure (Bishop et al., 2021; Warren et al., 2020). For the measurement of the single-leg CMJ height, a convenient and low-cost method using a smartphone application "My Jump" has been developed with strong validity and reliability reported (Haynes, Bishop, Antrobus, & Brazier, 2019). The entire movement of the single-leg CMJ can be recorded using a smartphone with 120-240 fps frame rate, and the jump height is calculated based on the flight time of the single-leg CMJ by identifying the take-off and landing frames in the "My Jump" application (Haynes et al., 2019).

For research, there is no consensus on which single-leg jump test to use for the assessment of inter-limb asymmetry in lower-limb power. Very strong reliabilities of the single-leg jump tests have been reported with the intraclass correlation coefficient (ICC) ranging from 0.81 to 0.99 (Bishop et al., 2021). Often multiple single-leg jump tests are used within research to assess inter-limb asymmetries in lower-limb power (Fort-Vanmeerhaeghe, Mila-Villarroel, Pujol-Marzo, Arboix-Alio, & Bishop, 2020; Read et al., 2018; Sieland et al., 2020; Warren et al., 2020). Barber, Noyes, Mangine, McCloskey, and Hartman (1990) have suggested the use of two single-leg hop tests when comparing jump performance between the involved and non-involved leg in clinical populations, because results have shown that the accuracy of evaluation dropped dramatically when using only one single-leg hop test in patients with anterior cruciate ligament (ACL) deficiency.

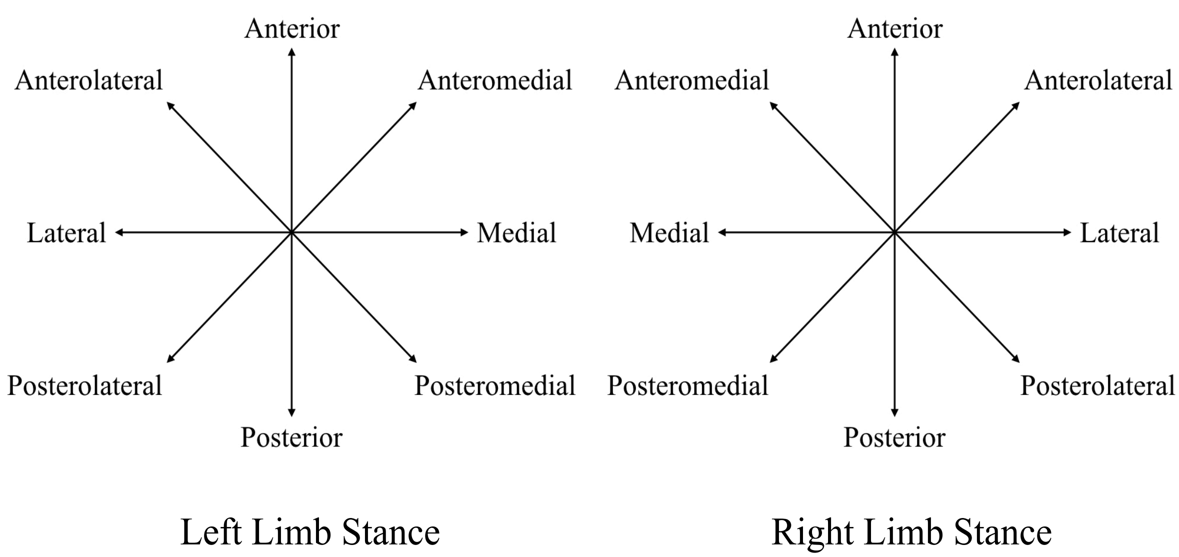
In contrast, bilateral jump tests are not suggested for research purposes because findings have demonstrated that inter-limb asymmetries in ground reaction force are not related in single-leg and two-leg CMJ (Benjanuvatra, Lay, Alderson, & Blanksby, 2013). Single-leg jump tests are recommended because the movements of single-leg jumps rely on the force generated from one side; the jump height and ground reaction force generated by the dominant and non-dominant leg separately were more indicative for the difference between the two sides (Benjanuvatra et al., 2013). Moreover, the single-leg drive/support is commonplace in sport movements including sprinting, jumping, jump landing, change of direction, and kicking (Benjanuvatra et al., 2013), which supports the utilization of single-leg jump tests in the assessment of inter-limb asymmetry in lower-limb power.

2.2.3 Dynamic balance tests

Inter-limb asymmetries in postural control have also been examined. Assessments for postural control can be grouped into static and dynamic balance tests (Gribble, Hertel, & Plisky, 2012; Pollock, 2010). Traditionally, in a static balance test, the task is to maintain a still stance on a firm surface (Hrysomallis et al., 2006). This provides information about the ability to maintain an upright posture and to keep the center of gravity within the limits of support, which is a basic characteristic of normal motor development (Bressel, Yonker, Kras, & Heath, 2007; Geuze, 2003). However, the limitation of a static balance test is that the task may not translate necessarily to most movement tasks in sports (Bressel et al., 2007; Gribble et al., 2012; Pollock, 2010), in which the balance is dynamically challenged, each time the athletes run, jump, or kick (Hrysomallis et al., 2006). In contrast, dynamic balance tests mimic the demands of sport movements more closely, although they do not exactly replicate the movements in sports (Gribble et al., 2012). In a dynamic balance test, the goal is to perform a task incorporating a dynamic movement or unstable surface, which challenges the ability to complete the task with great postural control in a dynamic situation (Hrysomallis et al., 2006). In the literature, inter-limb asymmetry in dynamic balance is often examined with the SEBT and the Y Balance Test.

The SEBT, originally developed by Gray (1995), offers a simple, reliable, and low-cost method for the assessment of dynamic balance (Olmsted et al., 2002). The goal of the SEBT is to obtain the maximum reach distance of the performer along the eight directions (Figure 2.1) using the contralateral limb while maintaining a unilateral stance with solid foundation (Olmsted et al., 2002). The reach directions are arranged 45º to each other, and named in orientation to the stance limb. While standing with a single leg at the convergence of reach direction lines, participants reach as far as possible with the reaching leg along each of the eight directions, lightly touching the lines with the most distal part of the reaching foot without disrupting the established balance during the entire test (Gribble et al., 2012). The reach distance in each direction is used for evaluating dynamic balance, and farther distances reached indicates better performance (Gribble et al., 2012). To quantify inter-limb asymmetries in SEBT performance, difference in reach distance between limbs at each reach direction is assessed.

Figure 2.1 Sketch of the reach directions in Star Excursion Balance Test (adapted from Bressel et al. (2007))



Hertel (2008) has recommended that only three reach directions are required (anterior, posteromedial, posterolateral) in SEBT. Analysis has shown high correlations between any reach distance and the seven other reach directions (Hertel, Braham, Hale, & Olmsted-Kramer, 2006). Further, factor analysis has shown that performance at the posteromedial reach direction identifies participants with chronic ankle instability (Hertel et al., 2006). Therefore, assessing three trials at each of the eight reach directions for each participant is likely redundant and not time efficient. Using three-directions of the SEBT (specifically, the anterior, posteromedial, and posterolateral directions) greatly simplifies administration of the test (Hertel et al., 2006). Plisky, Rauh, Kaminski, and Underwood (2006) reported that the composite score of the anterior, posteromedial, and posterolateral reach distances, as well as the inter-limb asymmetry in anterior reach distance, predicted lower-limb injury among high-school basketball athletes, which provides support for the use of the three-direction SEBT for injury prediction. A limitation of the SEBT is the lack of a standardized protocol (Coughlan, Fullam, Delahunt, Gissane, & Caulfield, 2012). Variations between protocols include whether the reaching foot touching floor is allowed, how much movement the standing foot is allowed, and the specific position of the standing foot (Plisky et al., 2009). These variations make it difficult to compare results between studies.

The Y Balance Test was developed to improve the standardization, repeatability, and efficiency of the SEBT (Plisky et al., 2009). Specifically, the Y Balance Test is a simplified version of the SEBT with three reach directions (anterior, posteromedial, and posterolateral) and standard testing procedure, using a device composed of three pieces of pipes extending in the anterior, posteromedial, and posterolateral directions (Plisky et al., 2009). Participants stand on the platform at the convergence of reach direction lines, and push the reach indicator along the pipe using the reaching foot at each direction, which allows easy operation of the test (Gribble et al., 2012). The Y Balance Test has been widely used for research and clinical purposes and reported with strong ICC and inter-tester reliability (Plisky et al., 2009).

2.2.4 Flexibility tests

Muscle flexibility has traditionally been evaluated using the range of motion of the joint, and a greater range of motion indicates greater flexibility of related muscles (Witvrouw, Danneels, Asselman, D'Have, & Cambier, 2003). Range of motion is commonly measured using a goniometer, which has been reported with strong inter-session reliability across seven common clinical flexibility tests (ankle dorsi-flexion with knee extended and flexed, straight leg raise, modified Thomas test, passive hip extension, hip flexion, and hip abduction) in futsal and handball athletes (Cejudo, de Baranda, Ayala, & Santonja, 2015). Inter-limb asymmetry in muscle flexibility is assessed by quantifying the difference in range of motion of the joint between the two sides. To date, studies have examined inter-limb asymmetries in lower-limb muscle flexibilities in a range of sports, including soccer (Daneshjoo, Rahnama, Mokhtar, & Yusof, 2013; Rahnama, Lees, & Bambaecichi, 2005), hockey (Cejudo et al., 2020), gymnastics (Batista, Garganta, & Ávila-Carvalho, 2019), fencing (Knapik et al., 1991), and tennis (Knapik et al., 1991).

2.2.5 Sport-specific tests

A number of studies have examined inter-limb asymmetries from a biomechanical perspective in sport-specific movements such as running (less than 4.4 $m \cdot s^{-1}$) (Brown, Zifchock, & Hillstrom, 2014), sprinting (Girard, Brocherie, Morin, & Millet, 2017), cycling (Bini & Hume, 2015; Liu & Jensen, 2012) and futsal (Barbieri, Gobbi, Santiago, & Cunha, 2015; Vieira et al., 2016). Reviewing related literature is difficult because of the differences between sports and parameters. For each sport, there could be a specific way to examine inter-limb asymmetry based on the specific movement. In running and sprinting, inter-limb asymmetries in kinetics and kinematics in ankle, knee, and hip joints (Brown et al., 2014), ground reaction force (Girard et al., 2017; Girard et al., 2020), vertical stiffness (Girard et al., 2017; Radzak, Putnam, Tamura, Hetzler, & Stickley, 2017), and muscle activation (Jacques, Bini, & Arndt, 2020) during the stance phase have been assessed. In cycling, inter-limb asymmetries in pedal force (Bini & Hume, 2015) and angular velocity of the ergometer's crank (Liu & Jensen, 2012) have been assessed. In futsal, inter-limb asymmetries in kicking accuracy, ball velocity, foot velocity, linear and/or angular joint velocity have been examined (Barbieri et al., 2015; Vieira et al., 2016).

2.2.6 Anthropometric tests

A wide range of parameters have been reported in the assessment of inter-limb asymmetry in anthropometrics. Summarizing and synthesizing the findings is difficult because of the differences between parameters. Moreover, studies have examined the inter-limb asymmetry in anthropometrics with various purposes, which also makes the reviewing difficult. To explore the effects of inter-limb asymmetry in anthropometrics on sport performance, Ujaković and Šarabon (2020) examined the functional leg length (distance between anterior-superior iliac spine and the ground when standing with feet separated hip distance apart) in elite basketball players using laser distance meter, and found that the asymmetry between the two sides was significantly associated with the change-of-direction performance. In addition, Kons, Diefenthaeler, et al. (2020) examined muscle thickness in rectus femoris and vastus lateralis for judo athletes using ultrasonography, and reported a negative correlation between inter-limb asymmetry in echo intensity in vastus lateralis and performance in a Special Judo Fitness Test. To explore the effects of sport training on inter-limb asymmetry in anthropometrics, Trivers et al. (2014) examined the knee joint width, ankle joint width, and foot length, and reported that widths of knee and ankle were more symmetrical between the two sides in elite track and field athletes in comparison with age-matched controls. Moreover, Frutuoso, Diefenthaeler, Vaz, and de la Rocha Freitas (2016) examined the thigh girth and estimated anatomical cross-sectional area in lower extremities in gymnastic athletes (aged 17.9 ± 4.0 y), and reported that the preferred leg showed larger thigh girth and anatomical cross-sectional area compared to the non-preferred leg. To explore the association between inter-limb asymmetry in anthropometrics and the inter-limb asymmetry in unilateral jump performance, Bell, Sanfilippo, Binkley, and Heiderscheit (2014) examined lean mass of the pelvis, thigh, and shank in collegiate athletes via dual-energy X-ray absorptiometry, and found that inter-limb asymmetries in thigh and shank lean mass explained 20% of the variance in bilateral CMJ force asymmetry, while inter-limb asymmetries in pelvis, thigh, and shank lean mass explained 25% of the variance in bilateral CMJ power asymmetry. To explore the effects of age on inter-limb asymmetry in anthropometrics, Mala et al. (2020) examined lower-limb muscle mass in soccer players using a multi-frequency bio-impedance analyzer, and found inter-limb asymmetry in lower-limb muscle mass was significant in U17 and adult players, but not in U12-U16 athletes.

2.2.7 Section summary

In summary, inter-limb asymmetries have been commonly assessed with a wide range of tests, including isometric and isokinetic strength tests, jump tests, dynamic balance tests, muscle flexibility tests, sport-specific tests, and anthropometric tests. The selection of tests for the assessment of inter-limb asymmetry should be based on the purpose of research. The information in this section provides a strong base for using the assessment of inter-limb asymmetry in areas including injury prediction and sports performance.

2.3 Calculating inter-limb asymmetry

A variety of equations for calculating inter-limb asymmetry have been proposed in the literature (Table 2.1). Typically, inter-limb asymmetry was presented as a percentage of difference between one limb with respect to the other (Bishop, Turner, et al., 2018; Hodges et al., 2011). It is important that the equation used for calculating inter-limb asymmetry matches the specifics of the test (Bishop, Read, Lake, Chavda, & Turner, 2018). However, there is no definitive conclusion on what the optimal equation is, especially when equations produce the same index (e.g., equation 1 and 2 [when the right leg is the dominant leg]). Bishop, Read, et al. (2018) reported that equation 3 (Asymmetry = [DL – NDL]/[DL + NDL] × 100 [%]) and 4 (Asymmetry = [stronger – weaker]/stronger × 100 [%]) were the optimal equations for calculating inter-limb asymmetry in bilateral and unilateral tests, respectively. For bilateral tests, it is essential to ensure the sum (the denominator) of the percentage of the dominant and non-dominant leg to be 100% in calculation; therefore, equation 3 would be the appropriate choice (Bishop, Read, et al., 2018). For the unilateral tests, the utilization of equation 4 is based on the assumption that taking the stronger side (the denominator) as 100% in calculation and expressing the difference between two sides as fractions of 100% (Bishop, Read, et al., 2018). However, it may not always be essential to take the stronger side as 100% when calculating inter-limb asymmetry in unilateral tests, and whether equation 4 is optimal for calculating inter-limb asymmetry in unilateral tests may need further discussion. In addition, Bishop, Read, Chavda, and Turner (2016) has suggested that equation 10 [Asymmetry = (45º - arctan[left/right])/90º × 100 (%)] may hold some advantages over other equations, because it is immune to reference values and inflated scores.

Table 2.1 Equations for calculating inter-limb asymmetry

Number	Equation	Reference
1	(DL – NDL) × 2/(DL + NDL) × 100 (%)	Marshall et al. (2015); Sugiyama et al. (2014); Wong et al. (2007)
2	(right – left) × 2/(right + left) × 100 (%)	Bell et al. (2014)
3	(DL – NDL)/(DL + NDL) × 100 (%)	Kobayashi et al. (2013)
4	(stronger – weaker)/stronger × 100 (%)	Impellizzeri, Rampinini, Maffiuletti, and Marcora (2007)
5	(high – low)/Total × 100 (%)	Sato and Heise (2012)
6	(left – right)/(maximum of left and right) × 100 (%)	Jordan et al. (2015)
7	(1 – NDL/DL) × 100 (%)	Schiltz et al. (2009); Sannicandro, Cofano, et al. (2014)
8	(1 – injured/non-injured) × 100 (%)	Schiltz et al. (2009)
9	weaker/stronger × 100 (%)	Ceroni et al. (2012)
10	(45º – arctan[left/right])/90º × 100 (%)	Zifchock, Davis, Higginson, McCaw, and Royer (2008)

DL, dominant leg; NDL, non-dominant leg.

The two sides of the lower extremities have been defined as dominant vs. non-dominant, right vs. left, stronger vs. weaker, high vs. low, or injured vs. non-injured legs in equations, and the difference in defining the two sides may impact the results. For example, equation 4 (Asymmetry = [stronger – weaker]/stronger × 100 [%]) and 5 (Asymmetry = [high – low]/total × 100 [%]) will ensure a positive value of inter-limb asymmetry; however, the inter-limb asymmetry can be a negative value when defining the two sides as the dominant vs. non-dominant leg (if the stronger/higher value was not from the dominant limb). Consequently, the methods of defining the two sides of limbs may have a prominent influence on the results. For sports requiring athletes to frequently perform asymmetrical movements (e.g., the lunge in fencing, squash, and badminton), the two sides of lower limbs were commonly defined as dominant vs. non-dominant leg, for the purpose of providing more context in reporting the inter-limb asymmetry (Bishop et al., 2016).

Inter-limb asymmetry is not always reported as a percentage of difference between the two sides. In the SEBT and Y Balance Test, inter-limb asymmetry has been mostly quantified using the absolute difference in reach distance (cm) between the two sides (Smith, Chimera, & Warren, 2015; Steinberg et al., 2020; Stiffler et al., 2017). In regard to the inter-limb asymmetry in muscle flexibility, a few studies have employed statistical analyses (e.g., paired *t* test) to examine the difference between the two sides (Cejudo et al., 2020; Daneshjoo et al., 2013; Rahnama et al., 2005); there are also studies using the absolute difference in range of motion (°) between the two sides to quantify the inter-limb asymmetry (Fousekis, Tsepis, Poulmedis, Athanasopoulos, & Vagenas, 2011; Fousekis, Tsepis, & Vagenas, 2012).

The amount of inter-limb asymmetry has been reported with a variable nature, and the standard deviation is usually close to or even greater than the mean (Bishop, McCauley, et al., 2019). Turner et al. (2015) has suggested that an inter-limb asymmetry can be considered as effective only if it is greater than the intra-limb variation (quantified using the coefficient of variation). However, the coefficient of variation of inter-limb asymmetry has been scarcely reported, which may be related to the fact that the calculation of the coefficient of variation for each participant is limited by the number of trials in each test (at least three trials needed). In practical application, studies often use the ICC to evaluate the reliability of data for each leg, and then calculate the inter-limb asymmetry based on an acceptable ICC of data in each leg (Fort-Vanmeerhaeghe et al., 2020; Plisky et al., 2006).

A deeper understanding of the calculation for inter-limb asymmetry will be beneficial to future research assessing inter-limb asymmetries. It is expected that an equation applied to most tests for assessing inter-limb asymmetries can be developed. To date, the inter-limb asymmetries reported across studies should be compared with caution, since the variation of calculations may impact the results.

2.4 Contributors to inter-limb asymmetry

2.4.1 Age and maturation

A number of studies have examined the effects of age on inter-limb asymmetry in jump performance in youth athletes (Madruga-Parera et al., 2019; Michailidis, Pirounakis, Savvakis, Margonis, & Metaxas, 2019; Sannicandro, Quarto, Piccinno, Cofano, & Rosa, 2014). Sannicandro, Quarto, et al. (2014) reported that 18.5% of a cohort of 11-y-old soccer athletes (aged 11.2 ± 0.1 y) showed >15% inter-limb asymmetry in side hop distance, while this percentage was 14.5% in 9-y-old athletes (aged 9.1 ± 0.1 y), suggesting that inter-limb asymmetry might be more notable in 11-y-old vs. 9-y-old soccer athletes. In contrast, Michailidis et al. (2019) reported that U10 players showed greater inter-limb asymmetry in single-leg CMJ height compared to that in U15 soccer players (3.69% vs. 1.73%). However, Madruga-Parera et al. (2019) reported no association between age and inter-limb asymmetry in single-leg CMJ performance in U12, U14, and U16 tennis athletes. Overall, findings are highly inconsistent; the development trend of inter-limb asymmetry in jump performance with increasing age in youth athletes is not clear. Although multiple age stages have been included, no study has involved athletes aged below 9 y. Research has shown that the participation by children aged ≤6 y increased from 9% in 1997 to 12% in 2008 among youth aged ≤18 y participating in organized sports in the United States (Malina, 2010), which indicates the necessity of examining inter-limb asymmetry in young children participating in sports.

Few studies have focused on the effects of age on inter-limb asymmetry in dynamic balance in youth athletes. Madruga-Parera et al. (2019) reported that the inter-limb asymmetry in posterolateral reach distance in the SEBT decreased with age (U12 [9.67%] vs. U14 [5.70%] vs. U16 [4.07%]) in tennis athletes, suggesting that inter-limb asymmetry in dynamic balance may decrease with increasing age in youth athletes. Future studies with participants across a wide range of age are needed.

Concerning the effects of maturation on inter-limb asymmetry, few studies are available in the literature. Madruga-Parera et al. (2019) has reported that inter-limb asymmetries in posteromedial and the composite reach distance of the three directions (anterior, posteromedial, and posterolateral) in the SEBT decrease with increasing maturation stage (pre, circa, and post-peak height velocity), suggesting that inter-limb asymmetry in dynamic balance may decrease with the progress of maturation in children and adolescent. This finding is consistent with the findings regarding the effects of age on inter-limb asymmetry in dynamic balance. These findings indicate that inter-limb asymmetry in dynamic balance may decrease with the progress of growth and maturation in children and adolescent. However, no association between the maturation stage and inter-limb asymmetry in jump performance was found (Madruga-Parera et al., 2019). In addition, as mentioned above, findings regarding the effects of age on inter-limb asymmetry in jump performance are highly inconsistent. Therefore, future studies need to further examine the development trend of inter-limb asymmetry in jump performance with the progress of growth and maturation.

2.4.2 Sex

Studies comparing inter-limb asymmetries in lower-limb isometric or isokinetic strength between females and males are listed in Table 2.2. Female athletes demonstrated significantly greater isometric strength (Brophy et al., 2009; Owens et al., 2011) and H/Q ratio (Kong & Burns, 2010; Pellicer-Chenoll et al., 2017) in the dominant leg compared to the non-dominant leg. For male athletes, no significant difference in isometric strength was found between limbs; however, the H/Q ratio was significant greater in the dominant leg compared to the non-dominant leg.

Table 2.2 Effects of sex on inter-limb asymmetries in lower-limb isometric/isokinetic muscle strength

Reference	Participants	Age (y)	Tests	Outcome measures and results
Brophy et al. (2009)	Collegiate soccer athletes	F: 20.8 ± 1.5 M: 21.6 ± 1.9	Isometric strength	Hip abductors strength F: DL > NDL, $p < 0.0001$ M: $p = 0.075$
Owens et al. (2011)	Collegiate athletes	Not reported	Isometric pull from mid-thigh	Peak force (DL vs. NDL) F: 13% asymmetry, $p < 0.05$ M: 6% asymmetry, $p > 0.05$
Pellicer-Chenoll et al. (2017)	Soccer athletes	F: 22.62 ± 4.69 M: 20.64 ± 4.69	Isometric and isokinetic strength	Isometric and isokinetic H/Q ratio F: DL > NDL, $p < 0.05$ M: DL > NDL, $p < 0.05$
Kong and Burns (2010)	High school athletes	F: 24.2 ± 7.4 M: 26.2 ± 5.0	Isometric and isokinetic strength	Isometric and isokinetic H/Q ratio F: DL > NDL, $p < 0.05$ M: DL > NDL, $p < 0.05$

F, female; M, male; DL, dominant leg; NDL, non-dominant leg; H/Q, hamstring/quadriceps.

Studies comparing inter-limb asymmetries in jump performance between females and males are listed in Table 2.3. Females showed greater inter-limb asymmetries in single-leg jump performance compared with males (Bampouras & Dewhurst, 2018; Fort-Vanmeerhaeghe et al., 2016). Supportively, Ceroni et al. (2012) reported that females were more likely to show >15% inter-limb asymmetry in jump kinetics compared to males. However, Stephens, Lawson, DeVoe, and Reiser (2007) reported contradictory results showing that inter-limb asymmetry in jump kinetics was found in males while not in females. The contradictory findings reported by Stephens et al. (2007) might be caused by the limited sample size as only 15 females and 13 males were included.

In jump landing, no significant difference in inter-limb asymmetry in peak vertical ground reaction force was found between males and females (Bell, Pennuto, & Trigsted, 2016), while females showed greater inter-limb asymmetry in knee valgus and ankle abduction compared with males (Ford et al., 2003; Pappas & Carpes, 2012).

Table 2.3 Effects of sex on inter-limb asymmetries in jump performance

Reference	Participants	Age (y)	Tests	Outcome measures and results
Bampouras and Dewhurst (2018)	Competitive team-game players	F: 20.8 ± 1.5 M: 21.6 ± 1.9	Single-leg 6-meter timed hop and triple hop	Asymmetry averaged across two tests F > M, $p = 0.039$ (9.1 ± 4.4% vs. 6.1 ± 3.5%)
Fort-Vanmeerhaeghe et al. (2016)	Professional basketball and volleyball athletes	F: 23.2 ± 4.4 M: 24.2 ± 4.7	Single-leg CMJ	Jump height asymmetry DL vs. NDL: F: 12.48%; M: 9.31%. Stronger vs. Weaker: F: 14.26%; M: 10.49%
Ceroni et al. (2012)	Healthy adolescents	F: 13.33 ± 1.93 M: 13.68 ± 1.87	Single-leg CMJ	Participants with > 15% asymmetry in peak vertical force: 25.5% F vs. 21.4% M Participants with asymmetry in maximum power: 32.7% F vs. 21.4% M
Stephens et al. (2007)	Recreational volleyball players	18-24	Single-leg vertical jumps	Peak GRF and ankle joint power F: $p > 0.05$ M: DL > NDL, $p < 0.05$
Bell, Pennuto, and Trigsted (2016)	Recreationally active students	18-23	Vertical jump landing	Peak vertical GRF asymmetry F: 14.55 ± 11.67% M: 16.68 ± 14.53% $p > 0.05$
Ford et al. (2003)	High-school basketball players	F: 16.0 ± 0.2 M: 16.0 ± 0.2	Drop jump	Knee valgus angle F: DL > NDL, $p = 0.001$ (27.6 ± 2.2° vs. 12.5 ± 2.8°) M: $p > 0.05$
Pappas and Carpes (2012)	Recreational athletes	F: 25.0 ± 3.0 M: 26.0 ± 2.0	Forward jump landing and drop jump	Knee valgus asymmetry in forward jump landing: F > M Ankle abduction asymmetry in drop jump: F > M

F, female; M, male; CMJ, countermovement jump; DL, dominant leg; NDL, non-dominant leg; GRF, ground reaction force.

Studies comparing inter-limb asymmetries in dynamic balance between females and males are listed in Table 2.4. Males demonstrated greater inter-limb asymmetry in anterior reach distance in the Y Balance Test compared to females; no significant difference was found between sexes in reach distance asymmetry at the other directions (Chimera, Smith, & Warren, 2015; Gorman, Butler, Rauh, Kiesel, & Plisky, 2012; Miller et al., 2017).

Table 2.4 Effects of sex on inter-limb asymmetries in dynamic balance

Reference	Participants	Age (y)	Tests	Reach distance asymmetry
Chimera et al. (2015)	Collegiate athletes	F: 20.0 ± 1.4 M: 20.0 ± 1.5	YBT	ANT: F < M, $p = 0.02$
Miller et al. (2017)	High-school athletes	15.6 ± 1.2	YBT	ANT: F < M, $p < 0.05$
Gorman et al. (2012)	High-school athletes	Not reported	YBT	ANT: F < M, $p < 0.03$

F, females; M, males; YBT, Y Balance Test; ANT, anterior.

In summary, females are more likely to show inter-limb asymmetries in lower-limb isometric strength and jump performance compared to males. However, males may show greater inter-limb asymmetries in dynamic balance compared to females. These findings imply that practitioners should pay attention to the difference between sexes when examining inter-limb asymmetry in lower-limb functional performance.

2.4.3 Sport

Sports like fencing, badminton, and tennis involve moving patterns that are highly asymmetrical in nature (Guan et al., 2018). In these sports, athletes perform large amount of lunge movement with the dominant leg performing as the leading leg and the non-dominant leg performing as the supporting leg (Guan et al., 2018). Over the long-term, the asymmetrical movement may lead to asymmetrical adaptations in the lower extremities (Hart et al., 2016). It has been reported that long-term exposure to asymmetrical loading in soccer resulted in different anthropometrical features between lower limbs (kicking vs. supporting leg), and greater exposure resulted in greater musculoskeletal adaptations (Hart et al., 2016). However, inter-limb asymmetries have also been reported in symmetrical sports such as running, swimming, and cycling (Maloney, 2019; Newton et al., 2006; Pappas et al., 2015). It has been suggested that inter-limb asymmetries occurring in symmetrical sports may result from limb preference (Loffing et al., 2016). More specifically, the preference for an individual's use of one limb may cause uneven development of neuromuscular function and flexibility in long-term sport training, which may result in inter-limb asymmetries in symmetrical sports (Loffing et al., 2016). To date, there is a lack of research examining the effects of lateral dominance in sport (asymmetrical [laterally dominant] vs. symmetrical [non-laterally dominant] sports) on lower-limb asymmetry. It is also difficult to compare the inter-limb asymmetries in asymmetrical vs. symmetrical sports reported across studies, due to the variety of tests administered and the various ways used for calculating inter-limb asymmetry.

2.4.4 Injury

The influence of previous injury on inter-limb asymmetry has been reported in the literature. Athletes with a previous injury may have reduced load on the affected leg, thereby using compensation from the contralateral leg to maintain sport performance (Webster, Austin, Feller, Clark, & McClelland, 2015). For example, individuals who have an ACL injury show an asymmetrical loading pattern with reduced load on the affected leg in double-leg movements including bilateral squat (Neitzel, Kernozek, & Davies, 2002; Salem, Salinas, & Harding, 2003; Webster et al., 2015), bilateral load squat (Castanharo et al., 2011), and bilateral CMJ (Castanharo et al., 2011). The inter-limb asymmetries still remain after completion of rehabilitation for the ACL injury and after returning to sports (Castanharo et al., 2011).

Supportive findings were reported by examining the effects of ACL injury on inter-limb asymmetry in single-leg movements. Males who had a previous ACL operation demonstrated greater sway range of center of pressure in the operated limb vs. non-operated limb in a 30-s single-leg stance (Clark, Bell, Feller, Whitehead, & Webster, 2017). Individuals who had an ACL injury 6-7 months before showed inter-limb asymmetry in kinematics (smaller knee and hip excursion in the involved side) and kinetics (smaller peak moment of knee flexion in the involved side) in walking gait (Di Stasi, Hartigan, & Snyder-Mackler, 2015; Di Stasi & Snyder-Mackler, 2012). Similarly, patients who had ACL construction 4-12 months before showed greater isometric strength of knee extension in the non-involved side than that in the involved side (Kuenze et al., 2019).

Cumulatively, these findings indicate that ACL injury is a significant factor contributing to inter-limb asymmetry in movements, while more studies are needed to focus on other injuries in addition to the ACL injury. Inter-limb asymmetries were mostly measured to assess the progress of rehabilitation in patients with ACL injury. Inter-limb asymmetry below 10% in lower-limb strength/power has been proposed as a cut-off value for injured athletes returning to sport (Kyritsis, Bahr, Landreau, Miladi, & Witvrouw, 2016; Rohman et al., 2015), although this is considered an arbitrary threshold.

2.4.5 Fatigue

A high injury rate, especially for non-contact injuries (e.g., ACL rupture), was reported during the latter stage of a professional football (Ekstrand et al., 2011) and rugby match (King, 2006). Exploring the effects of exercise-induced fatigue on inter-limb asymmetry may assist in further understanding the association between fatigue, inter-limb asymmetry, and sport injury.

A number of studies have examined the effects of exercise-induced fatigue on inter-limb asymmetry in running biomechanics; however, findings were inconsistent. Radzak et al. (2017) reported that inter-limb asymmetries in knee internal rotation excursion (from 15.37 to 29.40%) and knee stiffness (from 9.18 to 14.48%) increased at the fatigued state in healthy adults' running movement (4 ± 10% m/s), whereas the inter-limb asymmetries in vertical stiffness and loading rate decreased at the fatigued state. In contrast, most studies demonstrated no effect of fatigue on inter-limb asymmetries in running biomechanics (Brown et al., 2014; Girard et al., 2017; Girard et al., 2020; Jacques et al., 2020).

The effects of exercise-induced fatigue on inter-limb asymmetry in jump performance have also been examined. Bishop, McCauley, et al. (2019) reported that inter-limb asymmetry in single-leg CMJ height increased from 7.62% to 14.67% during a repeated sprint protocol (6 × 40-m sprint, 20-s rest between sprints, 4 sets) in active males. Similarly, Kons, Orssatto, et al. (2020) reported that inter-limb asymmetries in peak force, peak power, and mean power in single-leg CMJ increased after five sets of a stretch-shortening cycle fatigue protocol in male judo athletes. Additionally, Bromley et al. (2021) reported that inter-limb asymmetries in eccentric impulse and peak force in single-leg CMJ showed a large increase (12.24 to 32.00%, 14.71 to 31.85%, respectively) post soccer match in adolescent soccer athletes.

Based on these findings, it is suggested that fatigue may magnify inter-limb asymmetries in jump performance. However, there is a lack of research examining the effects of exercise-induced fatigue on inter-limb asymmetry in dynamic balance (SEBT or Y Balance Test performance) and in lower-limb muscle flexibility. Further, there is also a lack of research focusing on pediatric-age athletes.

2.4.6 Section summary

In summary, research has demonstrated the effects of sex, sport, previous injury, and fatigue on inter-limb asymmetries. Females are more likely to show inter-limb asymmetries in isometric strength and jump performance compared with males, while males may show greater inter-limb asymmetry in dynamic balance compared with females. Long-term sport training, previous injury, and fatigue may contribute to the increase in inter-limb asymmetry.

2.5 Inter-limb asymmetries in pediatric-age athletes

Compared with adult athletes, pediatric-age athletes are more vulnerable to sport injuries because of the stage of maturation of growth cartilage and the musculoskeletal system (Cuff et al., 2010; Radelet et al., 2002). Injuries in the growth cartilage may result in permanent alteration of bone and muscle growth if they were not properly treated (Radelet et al., 2002). To explore the effects of inter-limb asymmetry on risk of sport injury in pediatric-age athletes, it is important to examine the profile of inter-limb asymmetry in pediatric-age athletes.

Inter-limb asymmetries have primarily been assessed for lower-limb strength/power (Table 2.5), dynamic balance (Table 2.6), and lower-limb muscle flexibilities (Table 2.7) in pediatric-age athletes (≤17 y). Based on the findings listed in Table 2.5, single-leg CMJ and hop were mostly used to assess inter-limb asymmetries in lower-limb power in pediatric-age athletes. Research has demonstrated inter-limb asymmetries in lower-limb strength (isometric and isokinetic strength) and jump performance (bilateral and unilateral jump, drop jump, deep squat) in athletes aged from 9 to 17 y, while no evidence is available for athletes aged under 9 y.

Table 2.5 Inter-limb asymmetries in lower-limb strength/power in pediatric-age athletes

Reference	Participants	Tests	Asymmetry equation	Outcome measures and asymmetry
Rutkowska-Kucharska (2020)	Soccer players aged 16.9 ± 0.64 y	Isometric knee strength, bilateral vertical and horizontal jump	(right – left) × 2/(right + left) × 100 (%)	Isometric strength Knee flexors: 11.40 ± 7.84% Knee extensors: 10.50 ± 8.32% Bilateral jump GRF Vertical jump: 8.16 ± 5.44% Horizontal jump: 8.69 ± 7.03%
Ramos, Simão, Herdy, Costa, and Dias (2019)	Soccer players aged 15.97 ± 0.67 y	Isokinetic concentric and eccentric strength of hamstring and quadriceps	N/A	Eccentric strength of hamstring at 60^{o}/s: DL > NDL (*p* = 0.000); H/Q ratio at 60^{o}/s: DL > NDL (*p* = 0.009)
Bishop, Brashill, et al. (2019)	Elite male soccer players aged 15.1 ± 0.7 y	Single-leg CMJ	100/max value (right and left) × min value (right and left) × -1+ 100	Single-leg CMJ height: 9.02%
Madruga-Parera et al. (2019)	Elite tennis players aged 14.6 ± 2.7 y	Single-leg CMJ	(strong – weaker)/stronger × 100 (%)	Single-leg CMJ height: 14.71 ± 10.05%
Bishop et al. (2021)	Elite female soccer players aged 10 ± 1.1 y	Single-leg CMJ, hop, triple hop, crossover hop	100/max value (right and left) × min value (right and left) × -1+ 100	Single-leg CMJ height: 12.54%; Hop distance: 6.79% Triple-hop distance: 6.81% Crossover hop distance: 5.81%
Michailidis et al. (2019)	Male soccer players U10 (9.9 ± 0.3 y); U15 (14.6 ± 0.8 y)	Single-leg CMJ, hop, triple hop	(45^{o} – arctan[left/right])/90^{o} × 100 (%)	Single-leg CMJ height and hop distance U10 Single-leg CMJ: 3.69%; hop: 2.0%; triple hop: 2.33% U15 Single-leg CMJ: 1.73%; hop: 0.71%; triple hop: 0.17%
Michailidis et al. (2020)	Soccer players U10 (9.6 ± 0.3 y); U15 (14.1 ± 1.4 y)	Single-leg CMJ, hop, triple hop	(DL – NDL)/DL × 100 (%)	Single-leg CMJ height and hop distance U10 Single-leg CMJ: 10.38%; hop: 5.24%; triple hop: 6.94% U15 Single-leg CMJ: 5.63%; hop: 2.59%; triple hop: -0.14%
Bishop et al. (2020)	Elite female soccer players aged 15.9 ± 0.8 y	Single-leg CMJ, single-leg squat jump, unilateral drop jump	100/max value (right and left) × min value (right and left) × -1+ 100	Jump height Squat jump: 8.88 ± 7.73% Single-leg CMJ: 11.50 ± 8.80% Drop jump: 7.91 ± 4.73%

Reference	Participants	Tests	Asymmetry equation	Outcome measures and asymmetry
Pardos-Mainer, Casajús, and Gonzalo-Skok (2019)	Female soccer players aged 12.7 ± 0.6 y	Single-leg CMJ, hop, unilateral drop jump	(stronger – weaker/stronger) × 100 (%)	Control group Single-leg CMJ: 93.1 ± 4.35%; hop: 91.9 ± 6.37%; unilateral drop jump: 90.7 ± 5.94% Experimental group Single-leg CMJ: 90.0 ± 5.46%; hop: 92.9 ± 4.47%; unilateral drop jump: 87.1 ± 9.73%
Sannicandro, Cofano, et al. (2014)	Tennis players Experimental group: aged 13.2 ± 0.9 y; control group: 13.0 ± 0.9 y	Hop, side hop	(1 – NDL/DL) × 100 (%)	Experimental group Hop distance: 9.0 ± 3.6% Side hop distance: 10.8 ± 5.9% Control group Hop distance: 9.0 ± 3.7% Side hop distance: 13.2 ± 10.1%
Sannicandro, Quarto, et al. (2014)	Soccer players Group 1 aged 9.1 ± 0.1 y; group 2 aged 11.2 ± 0.1 y	Hop, triple hop, side hop	(1 – NDL/DL) × 100 (%)	Percentage of players with >15% asymmetry in hop distance Group 1 hop: 11.2%; triple hop: 8.4%; side hop: 14.5% Group 2 hop: 13.7%; triple hop: 8.3%; side hop: 18.5%
Ford et al. (2003)	High-school basketball players Females aged 16.0 ± 0.2 y; males aged 16.0 ± 0.2 y	Drop jump	N/A	Maximum valgus knee angle Females: DL (27.6 ± 2.2^{o}) > NDL (12.5 ± 2.8^{o}), $p < 0.001$ Males: no significant difference
Atkins, Bentley, Hurst, Sinclair, and Hesketh (2016)	Elite soccer players U13, U14, U15, U16, U17.	Deep squat	Not presented	Peak GRF U13: 6%; U14: 13%; U15: 11%; U16: 9%; U17: 4%

CMJ, countermovement jump; DL, dominant leg; NDL, non-dominant leg; H/Q, hamstring/quadriceps; GRF, ground reaction force; N/A, not applicable.

Table 2.6 Inter-limb asymmetries in dynamic balance performance in pediatric-age athletes

Reference	Participants	Tests	Outcome measures and asymmetry
Miller et al. (2017)	High-school athletes aged 15.6 ± 1.2 y	YBT	ANT reach distance asymmetry (cm) Multisport males: 3.10 ± 0.26 Single-sport males: 4.63 ± 0.50 Multisport female: 2.91 ± 0.23 Single-sport females: 2.75 ± 0.32
Lisman, Hildebrand, Nadelen, and Leppert (2019)	Male high-school athletes Age: injured 16.1 ± 1.3 y; non-injured 15.8 ± 1.4 y	YBT	Percentage of participants with reach distance asymmetry ≥ 4 cm ANT: 33.3%; PM: 55.8%; PL: 46.8%
Steinberg et al. (2020)	Female dancers aged 12-14 y	YBT	Reach distance asymmetry (cm) 12 years old ANT: 1.9 ± 1.7; PM: 3.7 ± 2.6; PL: 4.4 ± 4.8 13 years old ANT: 2.5 ± 1.8; PM: 5.7 ± 5.0; PL: 3.7 ± 2.4 14 years old ANT 2.6 ± 2.4; PM: 4.3 ± 3.7; PL: 7.4 ± 7.9
Gorman et al. (2012)	Single-sport athletes aged 15.9 ± 1.2 y; multiple-sport athletes aged 15.4 ± 1.2 y	YBT	Reach distance asymmetry (% leg length) Single-sport athletes ANT: 2.8 ± 2.2; PM: 4.6 ± 4.4; PL: 4.3 ± 4.3 Multiple-sport athletes ANT: 3.6 ± 3.8; PM: 4.3 ± 3.8; PL: 5.0 ± 4.2
Madruga-Parera et al. (2019)	Elite tennis players aged 14.6 ± 2.7 y	SEBT	Reach distance asymmetry (cm) ANT: 4.76 ± 3.16; PM: 4.22 ± 3.54; PL: 5.49 ± 3.95; COM: 3.49 ± 2.29
Pardos-Mainer et al. (2019)	Female soccer players aged 12.7 ± 0.6 y	YBT	Symmetry index Control group ANT: 96.1 ± 3.03%; PM: 89.8 ± 8.44%; PL: 90.4 ± 6.13% Experimental group ANT: 95.3 ± 4.65%; PM: 92.3 ± 7.48%; PL: 93.1 ± 5.53%

YBT, Y Balance Test; ANT, anterior; PM, posteromedial; PL, posterolateral; COM: composite score; SEBT, Star Excursion Balance Test.

Table 2.7   Inter-limb asymmetries in lower-limb muscle flexibility in pediatric-age athletes

Reference	Participants	Tests	Asymmetry equation	Outcome measures and asymmetry
Batista et al. (2019)	Gymnasts aged 13.3 ± 2.0 y	Passive and active flexibility in multiple joints	(DL – NDL)/DL × 100 (%)	Flexibility score averaged by lower-limb joints (asymmetry%) Passive flexibility: 23.0% Active flexibility: 31.6%
Ramos et al. (2019)	Soccer players aged 15.97 ± 0.67 y	Hip flexion	N/A	No significant difference between limbs
Pardos-Mainer et al. (2019)	Female soccer players aged 12.7 ± 0.6 y	Weight-bearing dorsiflexion	(stronger – weaker/stronger)× 100 (%)	Symmetry index Control group: 92.9 ± 4.94% Experimental group: 91.4 ± 5.65%

DL, dominant leg; NDL, non-dominant leg, N/A, not applicable.

Studies examining inter-limb asymmetries in dynamic balance in pediatric-age athletes are listed in Table 2.6. The SEBT and Y Balance Test were employed for assessing dynamic balance; reach distances at the anterior, posteromedial, and posterolateral direction in each leg were measured. Inter-limb asymmetries were mostly quantified using the absolute difference (cm) in reach distance between limbs at each direction. The results demonstrate that athletes aged from 12 to 17 y show inter-limb asymmetry in reach distance at each direction (anterior, posteromedial, posterolateral); no evidence is available for athletes below 12 y of age. It should be noted that the SEBT and Y Balance Test challenge the athlete’s physiological properties including strength, flexibility, proprioception, and balance (Gribble & Hertel, 2003; Johnston, Dolan, Reid, Coughlan, & Caulfield, 2018), which may be difficult for young children to complete. Moderate to good reliability of the SEBT in children aged 10-12 y has been reported (Calatayud, Borreani, Colado, Martin, & Flandez, 2014), although the appropriate age to administer the SEBT or Y Balance Test is not clear.

Few studies have examined the inter-limb asymmetry in lower-limb muscle flexibility in pediatric-age athletes (Table 2.7). Inter-limb asymmetries in passive and active range of motion in lower-limb joints (ankle, knee, and hip) have been reported with inconsistent results in athletes aged from 12 to 17 y, and it is difficult to make a clear statement. It should be noted that Batista et al. (2019) has reported a large amount of inter-limb asymmetry ([DL – NDL]/DL × 100 [%]) in passive (23.0%) and active (31.6%) flexibility score averaged by multiple lower-limb joints in gymnasts (aged 13.3 ± 2.0 y), suggesting that the inter-limb asymmetry in lower-limb muscle flexibility could be dramatic in pediatric-age athletes.

In summary, inter-limb asymmetries in lower-limb strength/power and dynamic balance have been widely reported in pediatric-age athletes. However, it is difficult to compare the amount of inter-limb asymmetry across studies, because of the difference in tests, parameters, and equations used for calculating asymmetry. Moreover, there is a lack of evidence about the profile of inter-limb asymmetry in lower-limb strength/power for athletes aged below 9 y, and the profile of inter-limb asymmetry in dynamic balance in athletes aged below 12 y.

2.6 Association between inter-limb asymmetries and sport injury

A strong focus on the inter-limb asymmetry is its association with sport injury. Focusing on lower extremities, inter-limb asymmetries have been associated with increased risk of sport injury because they may result in unequal force absorption or a loss of frontal plane stability, which are important to sustain the impacting forces (Paterno et al., 2010).

The effects of inter-limb asymmetries in lower-limb strength/power (Eagle et al., 2019; Izovska et al., 2019; Knapik et al., 1991) and dynamic balance (measured with the SEBT or Y Balance Test) (Brumitt et al., 2019; Lisman et al., 2019; Plisky et al., 2006; Smith et al., 2015) on sport injury have been widely examined. Studies have reported that a ≥15% inter-limb asymmetry in lower-limb strength/power indicates greater risk of sport injury (Bell et al., 2014; Impellizzeri et al., 2007; Knapik et al., 1991; Schiltz et al., 2009), while there is a lack of prospective-designed research examining this relationship. Inter-limb asymmetry in anterior reach distance greater than 4 cm in SEBT or Y Balance Test has also been associated with increased injury risk (Plisky et al., 2006; Smith et al., 2015); however, findings are not always consistent (Brumitt et al., 2019; Lisman et al., 2019). In addition, the inter-limb asymmetry in normalized reach distance (to leg length) in the SEBT has been associated with non-contact injuries to the knee or ankle (Stiffler et al., 2017); in contrast, Brumitt et al. (2019) reported no association between the normalized (to leg length) inter-limb asymmetry and non-contact lower-limb injury. The inconsistency in findings makes it difficult to draw a conclusion regarding the association between inter-limb asymmetry in dynamic balance and sport injury.

To date, limited research has focused on pediatric-age athletes. Further studies with a prospective design are warranted to investigate the association between inter-limb asymmetries and sport injury in pediatric-age athletes. In addition, a systematic overview and discussion of previous findings is missing so far. To systematically review previous findings will provide a better understanding of the role of inter-limb asymmetry in injury prediction.

2.7 Conclusions and future directions

Isometric/isokinetic strength tests, single-leg jump tests, and dynamic balance tests (the SEBT and Y Balance Test) are widely used assessments of inter-limb asymmetries in lower extremities in the literature. Inter-limb asymmetries reported across studies should be compared with caution due to the variety in equations for calculating asymmetry. Long-term sport training, previous injury, and fatigue potentially contribute to the development of inter-limb asymmetries. Significant inter-limb asymmetries in lower-limb strength/power and dynamic balance are shown in pediatric-age athletes, while there is a lack of research involving young children aged below 9 y. Future research needs to examine the profile of inter-limb asymmetry in young children as there is a trend of participating in sport training at a young age (≤6 y) in children (Malina, 2010). Inter-limb asymmetries in lower-limb strength/power and dynamic balance have been associated with increased risks of sport injury, but findings were not consistent, and few studies have focused on pediatric-age athletes.

Future research should examine the effects of lateral dominance in sports (asymmetrical vs. symmetrical sports) on inter-limb asymmetry. More prospective-design studies are needed to further examine the effects of inter-limb asymmetries in lower-limb strength/power and dynamic balance on sport injury due to the highly inconsistent findings in the current literature, and more studies are warranted to focus on pediatric-age athletes. Further research on the effects of fatigue on inter-limb asymmetries may provide a better understanding of the relationship between fatigue, inter-limb asymmetry, and sport injury.

Chapter 3: Association Between Inter-Limb Asymmetries in Lower-Limb Functional Performance and Sport Injury: A Systematic Review of Prospective Studies

This chapter provides a systematic review on published studies examining whether inter-limb asymmetry in lower-limb functional performance can predict sport injury. Findings in the literature were systematically summarized and synthesized to evaluate the validity of using inter-limb asymmetry in lower-limb functional performance for injury prediction, and to suggest directions for future research. Considerations for using inter-limb asymmetry in lower-limb functional performance to predict sport injury were also discussed.

3.1 Introduction

There is a growing attention on the association between inter-limb asymmetry in lower-limb functional performance and sport injury (Knapik et al., 1991; Plisky et al., 2006). Inter-limb asymmetry may potentially place both legs at an increased risk of injury in sports; the strong leg may sustain excessive stress due to high dependence and loading, whereas the weak leg may be compromised to sustain even average load (Ford et al., 2003). To date, the validity of using inter-limb asymmetries in lower-limb strength/power and dynamic balance to predict sport injury has been widely investigated. An ≥15% inter-limb asymmetry in lower-limb strength/power (Bell et al., 2014; Knapik et al., 1991) and ≥4 cm inter-limb asymmetry in anterior reach distance in the SEBT (Plisky et al., 2006) and Y Balance Test (Smith et al., 2015) have been associated with greater risk of sport injury. However, there are also a number of studies demonstrating no association between inter-limb asymmetry in lower-limb strength/power or dynamic balance (measured with the SEBT and Y Balance Test) and sport injury. In addition, a few studies have also examined the association between inter-limb asymmetry in lower-limb muscle flexibility and sport injury, and the findings were also inconsistent. Due to the high inconsistency of findings in literature, it is difficult to draw a conclusion about the validity of using inter-limb asymmetry in lower-limb functional performance for injury prediction.

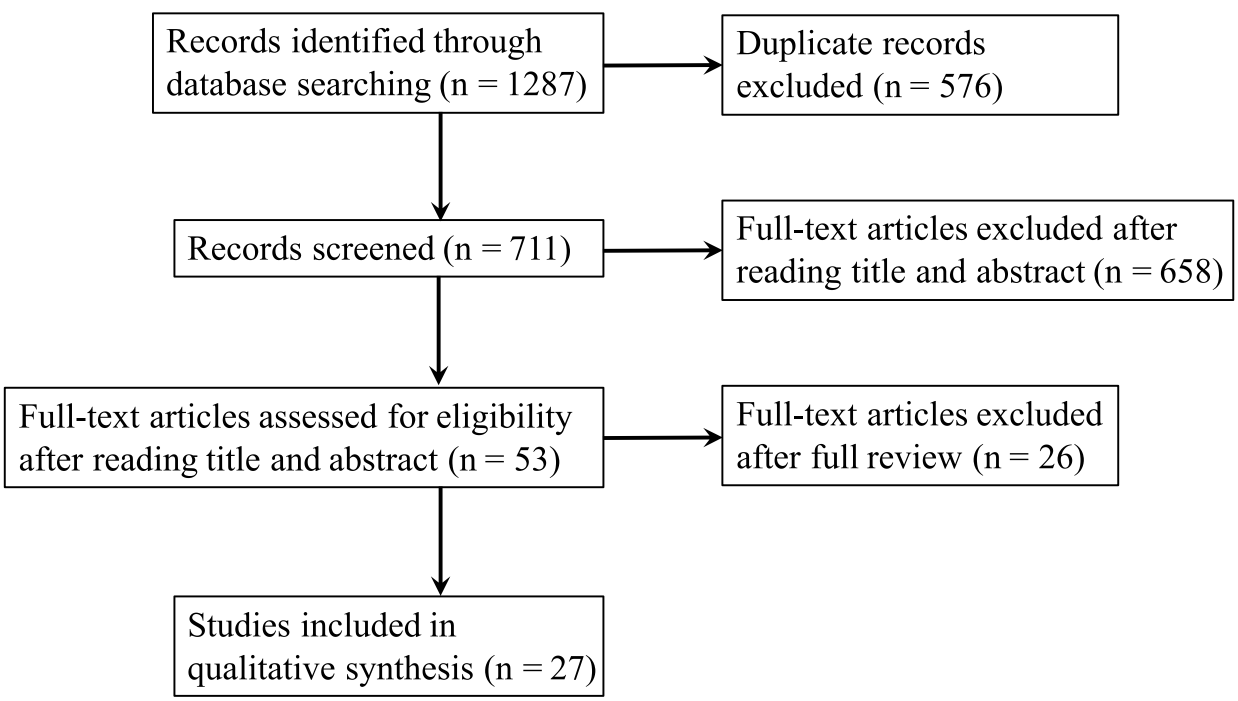
To systematically synthesize the results in the literature and analyze the factors contributing to the inconsistency of findings is essential; however, a systematic overview and discussion on previous findings is missing so far. Therefore, the aim of this study was to systematically review prospective studies examining whether inter-limb asymmetry in lower-limb functional performance (strength/power, dynamic balance, and muscle flexibility) can predict sport injury. The findings of this systematic review will provide a better understanding of the association between inter-limb asymmetry in lower-limb functional performance and sport injury, and guide future research.

3.2 Methods

3.2.1 Literature search

A systematic literature search was conducted in February 2021 to identify relevant trials. The search was performed in four databases: MEDLINE, EMBASE, Web of Science, and SportDiscus. An individualized search strategy was designed for each database. The search results from different databases were combined, and duplicates were removed. The titles and abstracts of the remaining articles were then checked, and unrelated publications were removed. Afterward, the full text of the remaining articles was checked for inclusion. Finally, reference lists of the included articles were manually checked for additional studies that were suitable for the present systematic review. Inclusion criteria required studies with a prospective design to examine the effects of inter-limb asymmetries in lower-limb power/strength, dynamic balance, or lower-limb muscle flexibility on risk of sport injury. Studies focusing on upper-limb or trunk asymmetries were excluded. Studies only reported inter-limb asymmetry for a sample without examining the association with sport injury were excluded. Studies focusing on the effects of injury on asymmetries, or the relationship between asymmetries and previous injuries were excluded. Reviews and articles not published in English were also excluded. The process of the study selection is demonstrated in Figure 3.1. The entire process adhered to the standards established by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) recommendations (Moher, Liberati, Tetzlaff, & Altman, 2010).

Figure 3.1 Flowchart of the searching process



3.2.2 Data extraction and analyses

The core features of the included studies were extracted, including participant characteristics, tests/tasks used for assessing inter-limb asymmetries, definition of injury, duration of follow-up, outcome measurements, equations for quantifying asymmetries, and results.

3.2.3 Study quality

A quality assessment was conducted based on a method reported previously (Bishop, Turner, et al., 2018; Black, Gabbett, Cole, & Naughton, 2016). The quality scoring system consists of nine criteria (Table 3.1) with a scale of 0-2 (0 represents “no”; 1 represents “maybe”; 2 represents “yes”). The quality score ranges from 0 to 18, with a higher score indicating a higher quality of the study. The quality score of each study was then converted to a percentage ranging from 0-100% (Table 3.1). Only studies scored above 75% would be included into the final analyses.

Table 3.1 Study quality scoring system (adapted from Black et al. (2016))

Criteria No.	Item	Score
1	Inclusion criteria stated	0-2
2	Subjects assigned appropriately	0-2
3	Intervention described	0-2
4	Dependent variables defined	0-2
5	Assessment practical	0-2
6	Training duration practical	0-2
7	Statistics appropriate	0-2
8	Results detailed (mean, standard deviation, effect size)	0-2
9	Conclusions insightful (clear, practical application, future directions)	0-2
	Total	0-18

3.3 Results

3.3.1 Search results

A total of 27 studies were included into analyses. Fourteen studies reported the association between inter-limb asymmetries in lower-limb power/strength and sport injury; three studies reported the association between inter-limb asymmetries in lower-limb muscle flexibility and sport injury; fifteen studies reported the association between inter-limb asymmetries in dynamic balance and sport injury. Studies examining inter-limb asymmetries in multiple tasks may be counted twice or more.

3.3.2 Participant characteristics

Eleven studies included both males and females; three studies only included females, and 12 studies only included males; two studies did not present information about the sex of the participants. Concerning participants' age, most studies included adult athletes, and only four studies focused on pediatric-age athletes (≤17 y). Four studies included both pediatric-age and adult athletes without separating them for analyses.

All studies included participants with a sporting background. In studies focusing on adult athletes, four included professional soccer athletes, 11 included collegiate athletes from a range of sports, one included collegiate students majored in physical education, and one included military recruits. Among the four studies focusing on pediatric-age athletes, one included handball, volleyball, and basketball athletes, two included soccer athletes, and one included ski racers. Only one study included athletes who had ACL reconstruction and returned to sport; all the other studies included healthy athletes. The number of participants in a study ranged from 45 to 362.

3.3.3 Tests and outcome measurements

Characteristics of the 14 studies focusing on lower-limb strength/power are listed in Table 3.2. Seven studies examined inter-limb asymmetries in unilateral jump performance, including single-leg CMJ, hop, triple hop, and crossover hop. Outcome measurements included the vertical height of the single-leg CMJ and the horizontal distance of the hops. One study measured the biomechanics (e.g., peak vertical ground reaction force) during the single-leg CMJ; one study examined inter-limb asymmetries in biomechanics in bilateral drop vertical jump. In addition, five studies examined inter-limb asymmetries in lower-limb strength with isometric strength tests; five studies examined this with isokinetic strength tests. In isometric and isokinetic strength tests, outcome measurements mainly included concentric and eccentric strength of the lower-limb joints.

Three studies examined the association between inter-limb asymmetries in lower-limb muscle flexibilities and sport injury (Table 3.2). Outcome measurements included the range of motion (°) in ankle, knee, and hip measured with a goniometer.

Table 3.2 Study characteristics – inter-limb asymmetries in lower-limb strength/power and muscle flexibility

Reference	Participants	Tasks and outcome measures	Injury	Duration of follow-up	Quality score
Brumitt et al. (2013)	193 collegiate athletes	Single-leg hop distance	Low back or lower-limb injury (≥ 1-d time loss)	1 season	16
Brumitt, Mattocks, Loew, and Lentz (2020)	82 female collegiate volleyball players	Single-leg hop distance	Non-contact injury to low back or lower limbs (≥ 1-d time loss)	1 season	16
Read et al. (2018)	357 elite male youth soccer players (aged 10-18 y)	Single-leg CMJ and hop	Non-contact lower-limb injury (≥ 48-hr time loss)	10 mos	17
Fort-Vanmeerhaeghe et al. (2020)	81 young elite team-sport athletes (U14-U18)	Single-leg CMJ and hop	Non-contact injury	1 season	17
Warren et al. (2020)	68 female collegiate athletes	Single-leg hop, triple-hop, and crossover distance	Non-contact lower-limb and spine injury requiring intervention by athletic trainer	1 y	17
Paterno et al. (2010)	56 young athletes (aged 16.41 ± 2.97 y who had ACL reconstruction and returned to sport	Bilateral drop vertical jump	Second ACL injury	1 y	15
Sieland et al. (2020)	250 male youth elite soccer players (13.5 ± 4.5 y)	Single-leg CMJ and hop, isometric knee extension and flexion strength	≥ 1-d time loss injury	2 seasons	15
Steidl-Muller et al. (2018)	95 youth (10-14 y), 107 adolescent (15-19 y), and 83 elite adult (20-34 y) ski racers	Single-leg CMJ, isometric/isokinetic knee extension strength	Traumatic and overuse injury (≥1-d time loss)	2 seasons	18
De Blaiser et al. (2021)	142 collegiate physical education students	Isometric hip strength	Non-contact, acute lower-limb injury	1.5 y	17
Hietamo et al. (2021)	Team-sport athletes aged ≤ 21 y (188 males, 174 females)	Isokinetic (60º/s) quadriceps and hamstring strength; isometric hip abductor strength	Acute ankle injury (≥ 1-d time loss)	1 y	16

Reference	**Participants**	**Tasks and outcome measures**	**Injury**	**Duration of follow-up**	**Quality score**
Markovic et al. (2020)	45 professional outfield male soccer players	Isometric hip adductor strength	Groin injury	1 season	18
Fousekis et al. (2011)	100 professional male soccer players	Isokinetic knee strength; knee and ankle flexibility	Non-contact hamstrings and quadriceps strains (≥ 1-d time loss)	10 mos	17
Fousekis et al. (2012)	100 professional male soccer players	Isokinetic (60º/s) ankle strength; ankle flexibility	Non-contact ankle sprain	10 mos	17
Knapik et al. (1991)	138 female collegiate athletes	Isokinetic (30 and 180º/s) knee strength; ankle, knee, and hip flexibility	Time-loss injury	1 y	15

CMJ, single-leg countermovement jump; ACL, anterior cruciate ligament.

Characteristics of the 15 studies focusing on dynamic balance (measured with the SEBT and Y Balance Test) are listed in Table 3.3. Reach distances at the anterior, posteromedial, and posterolateral direction were measured for each leg. Inter-limb asymmetry in reach distance at each direction was calculated.

Table 3.3 Study characteristics – inter-limb asymmetries in dynamic balance

Reference	Participants	Tasks and outcome measures	Injury	Duration of follow-up	Quality score
Brumitt et al. (2019)	169 male collegiate basketball players	ANT, PM, PL reach distance in YBT	Non-contact low-back or lower-limb injury (≥ 1-d time loss)	1 season	15
Brumitt, Sikkema, et al. (2020)	214 collegiate athletes	ANT, PM, PL reach distance in YBT	Non-contact low-back or lower-limb injury (≥ 1-d time loss)	1 season	16
Butler et al. (2013)	59 collegiate American football players (males)	ANT, PM, PL reach distance in YBT	Non-contact lower-limb injury (≥ 1-d time loss)	1 season	15
De Blaiser et al. (2021)	142 physical education students	ANT, PM, PL reach distance in SEBT	Non-contact, acute lower-limb injury	1.5 y	17
Gonell et al. (2015)	74 male soccer players	ANT, PM, PL reach distance in YBT	Lower-limb injury (≥ 1-d time loss)	1 season	18
Hartley, Hoch, and Boling (2018)	Collegiate athletes (284 males and 167 females)	ANT, PM, PL reach distance in YBT	Ankle sprain injury	2 ys	17
Lai et al. (2017)	294 collegiate athletes	ANT, PM, PL reach distance in YBT	Lower-limb injury (≥ 7-d time loss)	1 season	16
Lisman et al. (2019)	124 high-school athletes (injured group aged 16.1 y; uninjured group aged 15.8 y)	ANT, PM, PL reach distance in YBT	Lower-limb injury (≥ 1-d time loss)	4 mos	18
Luedke, Geisthardt, and Rauh (2020)	59 male collegiate American football players	ANT, PM, PL, and COM reach distance in YBT	Non-contact lower-limb or lower-back injury (≥ 1-d time loss)	1 season	17
Manoel, Xixirry, Soeira, Saad, and Riberto (2020)	89 professional male soccer athletes	ANT, PM, PL reach distance in YBT	Time-loss injury	1 season	16
Nakagawa et al. (2020)	135 male military recruits	ANT, PM, PL reach distance in YBT	Patellofemoral pain	6 wks	17
Plisky et al. (2006)	235 high-school basketball players	ANT, PM, PL reach distance in SEBT	Lower-limb injury (≥ 1-d time loss)	1 season	17

Reference	Participants	Tasks and outcome measures	Injury	Duration of follow-up	Quality score
Read et al. (2020)	346 elite male youth soccer players (age: pre PHV, 11.9 ± 1.1 y; circa PHV, 14.4 ± 0.9 y; post PHV, 16.1 ± 1.1 y)	ANT reach distance in YBT	Non-contact lower-limb injury (≥ 48-hr time loss)	1 season	17
Ruffe, Sorce, Rosenthal, and Rauh (2019)	148 cross-country athletes aged between 13 and 19 years	ANT, PM, PL reach distance in YBT	Low back or lower-limb injury (≥ 1-d time loss)	1 season	16
Smith et al. (2015)	200 collegiate athletes	ANT, PM, PL reach distance in YBT	Non-contact injury	1 season	17

ANT, anterior; PM, posteromedial; PL, posterolateral; YBT, Y Balance Test; SEBT, Star Excursion Balance Test; COM, composite; PHV, peak height velocity.

3.3.4 Definition of injury

The definition of injury varies across studies due to the difference in mechanism of injury (non-contact vs. contact injury), duration of time loss, and included locations of injury. Concerning the mechanism of injury, most studies only included non-contact injuries, while the other studies also included contact injuries. For the location of injury, most studies focused on lower-limb injury or injury occurred to a certain part of the lower extremities (e.g., groin, ankle). In regard to the requirement of time loss, most studies only included injuries leading to time loss from sport participation or training; the duration of time loss was usually one day or longer. In addition, the duration of follow-up for injury collection ranged from 1-2 seasons or 10-18 months; however, the specific duration of a season was not always clearly defined.

3.3.5 Calculation of asymmetries

A variety of equations were employed to calculate inter-limb asymmetries in lower-limb power/strength (Table 3.4). These asymmetries were commonly calculated as a percentage of difference between one limb with respect to the other. Six different equations were used in eight studies to quantify the inter-limb asymmetry as a percentage; one study used the absolute difference (cm) in hop distance between the two sides (Warren et al., 2020); five studies did not present the method of calculating inter-limb asymmetry.

Regarding the inter-limb asymmetry in lower-limb muscle flexibility (Table 3.4), two studies used the absolute difference in range of motion (°) between the two sides (Fousekis et al., 2011; Fousekis et al., 2012); the other study quantified the inter-limb asymmetry as a percentage (right divided by left) of difference between the two sides (Knapik et al., 1991).

Regarding the inter-limb asymmetries in dynamic balance (Table 3.5), most studies used the absolute difference (cm) of reach distance between the two sides (at each reach direction). Only one study normalized the reach distance to leg length (leg length%) and quantified both the absolute (cm) and normalized (%) inter-limb asymmetry (Brumitt et al., 2019).

Table 3.4 Study results – inter-limb asymmetries in lower-limb strength/power and muscle flexibility

Reference	**Variables of interest**	**Equations for calculating Asymmetry**	**Findings**
Brumitt et al. (2013)	Single-leg hop distance	Low/high × 100 (%)	10% hop asymmetry associated with greater risk of foot and ankle injury in female collegiate athletes (OR = 4.4, $p < 0.05$)
Brumitt, Mattocks, et al. (2020)	Single-leg hop distance	Not reported	10% hop asymmetry not associated with injury in female collegiate volleyball players ($p > 0.05$)
Read et al. (2018)	Biomechanics in single-leg CMJ and hop	(Low – high)/high × 100 (%)	Single-leg CMJ peak landing vertical GRF asymmetry (U11-12, OR = 0.90, $p = 0.04$; U15-16, OR = 0.91, $p < 0.001$) associated with non-contact lower-limb injury male youth soccer athletes
Fort-Vanmeerhaeghe et al. (2020)	Single-leg CMJ height, hop distance	(High – low)/high × 100 (%)	Non-injured young team-sport athletes showed lower SLCMJ height asymmetry ($p = 0.00$) vs. injured athletes
Warren et al. (2020)	Single-leg hop, triple-hop, and crossover hop distance	Absolute difference between limbs	Triple-hop distance asymmetry (OR [>12 vs. ≤12 cm] = 7.31, $p < 0.05$) associated with greater risk of lower-body (lower limb and spine) injury in female collegiate athletes
Paterno et al. (2010)	Internal knee extensor moment at initial contact in drop vertical jump	Not reported	Internal knee extensor moment asymmetry at initial contact (OR = 3.3, p not reported) associated with second ACL injury in young athletes with ACL reconstruction and returning to sport
Sieland et al. (2020)	Single-leg CMJ height and hop distance	Dominant/non-dominant × 100 (%)	Injured male youth soccer athletes showed greater SL-hop distance asymmetry vs. non-injured athletes ($p = 0.027$ adjusted for age)
Steidl-Muller et al. (2018)	Single-leg CMJ height, isometric/isokinetic knee extension strength	Dominant/non-dominant × 100 (%)	Isometric knee extension strength asymmetry (Wald = 7.08, $p < 0.01$) associated with traumatic injury in 10-14 years ski racers

Reference	Variables of interest	Equations for calculating Asymmetry	Findings
De Blaiser et al. (2021)	Isometric strength in hip abduction	Weaker/stronger × 100 (%)	Hip abduction strength asymmetry associated with acute lower-limb injury in collegiate physical education students (HR = 0.941, p = 0.007)
Hietamo et al. (2021)	Isometric hip abductor strength	Not reported	Hip abductor strength asymmetry (HR = 1.44, $p < 0.05$) associated with greater risk of acute ankle injury in young athletes
Markovic et al. (2020)	Isometric hip adductor torque	Left/right	Adductor strength asymmetry (p = 0.09) not associated with groin injury in professional soccer players
Fousekis et al. (2011)	Isokinetic concentric and eccentric hamstring and quadriceps strength; quadriceps flexibility	Strength: not reported Flexibility: right – left	≥15% eccentric hamstring strength asymmetry (OR = 3.88, p = 0.03) associated with greater risk of hamstring strain in professional soccer players ≥15% eccentric quadriceps strength asymmetry (OR = 5.02, p = 0.06), ≥6º quadriceps flexibility asymmetry (OR = 4.98, p = 0.08) associated with greater risk of quadriceps strain in professional soccer players
Fousekis et al. (2012)	Isokinetic concentric and eccentric strength in ankle dorsal and plantar flexors; ankle flexibility	Strength: not reported Flexibility: right – left	≥15% asymmetry in eccentric ankle flexion strength (OR = 8.88, p = 0.005) associated with greater risk of ankle sprain in professional soccer players
Knapik et al. (1991)	Isokinetic knee flexor strength; hip extensor flexibility	Right/left	More injuries occurred in female collegiate athletes when 1) right > left knee flexor strength (180º/s) by 15% (chi square, 9.5; p = 0.005) 2) right > left hip extensor flexibility by 15% (chi square, 10.71; $p < 0.001$)

OR, odds ratio; CMJ, countermovement jump; GRF, ground reaction force; ACL, anterior cruciate ligament; HR, hazard ratio

3.3.6 Inter-limb asymmetries in lower-limb strength/power and injury

Four studies examined the validity of using inter-limb asymmetries in single-leg CMJ performance to predict sport injury with inconsistent findings reported. Two studies demonstrated no association between inter-limb asymmetry in single-leg CMJ height and time-loss injury in U12-U19 male soccer players (Sieland et al., 2020) or 10-14 y old ski racers (Steidl-Muller et al., 2018). In contrast, Fort-Vanmeerhaeghe et al. (2020) reported that the non-injured group showed smaller inter-limb asymmetry in single-leg CMJ height compared to the injured (non-contact injury) group in U14-U18 athletes; Read et al. (2018) reported that the inter-limb asymmetry in peak landing vertical ground reaction force in single-leg CMJ was associated with non-contact lower-limb injury in U11-U12 and U15-U16 soccer athletes.

Six studies examined the validity of using inter-limb asymmetries in single-leg hop and triple hop distance to predict sport injury, reporting inconsistent findings. Three studies demonstrated an association between inter-limb asymmetry in hop distance and injury. Brumitt et al. (2013) reported that ≥10% inter-limb asymmetry in single-leg hop distance indicated greater risk of foot and ankle injury in female volleyball players. Supportively, Warren et al. (2020) reported that ≥12 cm inter-limb asymmetry in triple-hop distance indicated greater risk of lower-limb and spine injuries in female collegiate athletes. Additionally, by comparing non-injured and injured U12-U19 male soccer athletes, Sieland et al. (2020) reported that injured (time-loss injury) athletes showed greater inter-limb asymmetry in single-leg hop distance compared to non-injured athletes. Conversely, the other three studies demonstrated no association between inter-limb asymmetry in single-leg hop distance and non-contact lower-limb injury in U11-U16 male soccer athletes (Read et al., 2018), non-contact injury in U14-U18 team-sport athletes (Fort-

Vanmeerhaeghe et al., 2020), or non-contact lower-limb injury in collegiate athletes (Brumitt, Mattocks, et al., 2020).

Four studies examined the validity of using inter-limb asymmetries in isometric strength to predict sport injury. Steidl-Muller et al. (2018) reported an association between inter-limb asymmetry in isometric knee extension strength and traumatic injury in 10-14 y old ski racers. Similarly, inter-limb asymmetry in isometric hip abduction strength has also been associated with acute ankle injury in youth athletes aged below 21 y (Hietamo et al., 2021) and acute lower-limb injury in collegiate physical education students (De Blaiser et al., 2021). However, Markovic et al. (2020) demonstrated no association between inter-limb asymmetry in isometric hip adductor strength and groin injury in professional male soccer athletes.

Three studies examined the validity of using inter-limb asymmetries in isokinetic strength to predict sport injury with consistent findings reported. Fousekis et al. (2011) reported that ≥15% inter-limb asymmetry in isokinetic eccentric hamstrings and quadriceps strength indicated greater risk of hamstring and quadriceps strain, respectively. Similarly, Fousekis et al. (2012) reported that ≥15% inter-limb asymmetry in eccentric ankle flexion strength indicated greater risk of ankle sprain. Moreover, Knapik et al. (1991) reported that more injuries occurred when the right knee flexor strength was 15% stronger than the left.

3.3.7 Inter-limb asymmetries in lower-limb muscle flexibility and injury

Three studies examined the effects of inter-limb asymmetries in lower-limb muscle flexibility on sport injury, reporting inconsistent findings (Table 3.4). Knapik et al. (1991) reported that more injuries occurred in female collegiate athletes when the right knee extensor was 15% more flexible than the left. Fousekis et al. (2011) reported that ≥6º inter-limb asymmetry in quadriceps flexibility indicated greater risk of quadriceps strain in professional soccer players. However, two studies demonstrated no effect of inter-limb asymmetry in ankle (Knapik et al., 1991) or knee flexibility (Fousekis et al., 2011) on sport injury in professional soccer athletes.

3.3.8 Inter-limb asymmetries in dynamic balance and injury

Among the 15 studies focusing on inter-limb asymmetries in dynamic balance (measured by the SEBT or Y Balance Test), only six reported a significant relationship between inter-limb asymmetry and injury (Table 3.5). Smith et al. (2015) reported that ≥4 cm inter-limb asymmetry in anterior reach distance in Y Balance Test indicated greater risk of non-contact injury in collegiate athletes; Read et al. (2020) reported that increased asymmetry in anterior reach distance in Y Balance Test indicated increased injury risk in youth male soccer players. For the posteromedial reach distance, research showed that ≥4 cm asymmetry between limbs in SEBT indicated greater risk of lower-limb injury in high-school basketball athletes (Plisky et al., 2006), in 13-19 y old cross-country athletes (Ruffe et al., 2019), and in adult male soccer athletes (Gonell et al., 2015). For the posterolateral reach distance, research showed that ≥4.08 cm inter-limb asymmetry in Y Balance Test indicated greater risk of patellofemoral pain in male military recruits (Nakagawa et al., 2020). However, the other nine studies demonstrated no association between inter-limb asymmetry in dynamic balance (reach distance measured in the SEBT and Y Balance Test) and sport injury.

Table 3.5 Study results – inter-limb asymmetries in dynamic balance

Reference	Variables of interest	Calculation for asymmetry	Findings
Brumitt et al. (2019)	ANT, PM, and PL reach distance asymmetry	Absolute difference and the normalized difference to leg length	No association between asymmetries and injury in male collegiate basketball players (RR = 0.9-1.2, $p > 0.05$)
Brumitt, Sikkema, et al. (2020)	ANT, PM, and PL reach distance asymmetry	Not reported	No association between asymmetries and injury in collegiate athletes (no cut-off value in ROC curve)
Butler et al. (2013)	ANT, PM, and PL reach distance asymmetry	Absolute difference	No association between asymmetries and injury (no cut-off value in ROC curve) in collegiate American football players
De Blaiser et al. (2021)	ANT, PM, and PL reach distance asymmetry	Absolute difference	No association between asymmetries and injury in university physical education students ($p > 0.05$)
Gonell et al. (2015)	ANT, PM, and PL reach distance asymmetry	Absolute difference	≥4 cm PM reach distance asymmetry (OR = 3.86, $p = 0.001$) associated with greater risk of lower-limb injury in male soccer players
Hartley et al. (2018)	ANT, PM, and PL reach distance asymmetry	Absolute difference	No association between asymmetries and ankle sprain injury in female collegiate athletes ($p > 0.05$)
Lai et al. (2017)	ANT, PM, and PL reach distance asymmetry	Absolute difference	No association between asymmetries and lower-limb injury in collegiate athletes ($p > 0.05$)
Lisman et al. (2019)	ANT, PM, and PL reach distance asymmetry	Absolute difference	No association between asymmetries and lower-limb injury in high school athletes ($p > 0.05$)
Luedke et al. (2020)	ANT, PM, PL, and COM reach distance asymmetry	Absolute difference	No association between asymmetries and lower-limb or lower-back injury in collegiate American football players ($p > 0.05$)
Manoel et al. (2020)	ANT, PM, and PL reach distance asymmetry	Absolute difference	No association between asymmetries and ankle injury in professional male soccer players ($p > 0.05$)
Nakagawa et al. (2020)	ANT, PM, and PL reach distance asymmetry	Absolute difference	≥4.08 cm PL reach distance asymmetry (OR = 5.46, $p < 0.001$) associated with patellofemoral pain in male military recruits
Plisky et al. (2006)	ANT, PM, and PL reach distance asymmetry	Absolute difference	≥4 cm PM reach distance asymmetry (OR = 2.3, $p < 0.05$) associated with greater risk of lower-limb injury in high-school basketball players
Read et al. (2020)	ANT reach distance asymmetry	Absolute difference	ANT reach distance asymmetry associated with non-contact lower-limb injury in male youth soccer players (pre-PHV: OR = 0.94, $p < 0.05$; circa-PHV: OR = 1.05, $p < 0.05$)

Reference	Variables of interest	Calculation for asymmetry	Findings
Ruffe et al. (2019)	ANT, PM, and PL reach distance asymmetry	Absolute difference	≥4 cm PM reach distance asymmetry (OR = 5.05, $p = 0.02$) associated with greater risk of lower-limb or low back injury in young cross-country athletes
Smith et al. (2015)	ANT, PM, and PL reach distance asymmetry	Absolute difference	≥4 cm ANT reach distance asymmetry (OR = 2.20, $p = 0.03$) associated with greater risk of non-contact injury in collegiate athletes

ANT, anterior; PM, posteromedial; PL, posterolateral; RR, relative risk; ROC, receiver operating characteristic; OR, odds ratio; COM, composite; PHV, peak height velocity.

3.4 Discussion

This main purpose of this systematic review was to summarize findings of research examining whether inter-limb asymmetries in lower-limb strength/power, dynamic balance, and muscle flexibility can predict sport injury. Mixed findings have been reported, and it is difficult to make a clear statement about the validity of using inter-limb asymmetry to predict sport injury. Findings were highly inconsistent due to the variations in research methodology across studies. A number of considerations (difference in tests, participant characteristics, definition of injury, and ways of calculating asymmetries) are required to infer recommendations for future research. These considerations and potential influence on findings will be discussed in this section.

3.4.1 Tests/tasks

Inter-limb asymmetry in each function (strength/power, flexibility, dynamic balance) has been assessed with a variety of tests. It is difficult to compare the amount of inter-limb asymmetry generated from different tests. Even using the same test, it is also difficult to compare the amount of inter-limb asymmetry between studies using different parameters (e.g., jump height vs. peak ground reaction force during landing in unilateral CMJ). The difference in selection of tests may result in inconsistent findings, especially when using the cut-off values for injury prediction. For example, ≥15% inter-limb asymmetry in isokinetic strength of knee extensor, knee flexor (Fousekis et al., 2011), and ankle flexor (Fousekis et al., 2012) have been associated with greater risk of injury; however, this association was not shown when using ≥15% inter-limb asymmetry in isometric hip strength (De Blaiser et al., 2021; Markovic et al., 2020) or unilateral jump tests (Brumitt et al., 2013; Brumitt, Mattocks, et al., 2020) to predict injury. Therefore, before comparing findings between studies, it is important to consider the difference between tests (and parameters).

Most studies assessed inter-limb asymmetries in lower-limb strength/power using isometric strength tests, isokinetic strength tests, unilateral jump tests, and bilateral jump tests. However, the isometric and isokinetic strength tests may not be the optimal tests for sports characterized by quick muscle actions involving stretch-shortening cycle (Impellizzeri et al., 2007). Instead, jump tests are recommended for the assessment of lower-limb strength/power because of the required stretch-shortening cycle and high-rate force production (Impellizzeri et al., 2007). Especially, unilateral jumps are recommended because the movements of unilateral jumps rely on the force generated from one side, and the performance of the dominant and non-dominant side separately were more indicative for the difference between the two sides (Benjanuvatra et al., 2013). Moreover, the single-leg drive/support is common in movements including sprinting, jumping, jump landing, change of direction, and kicking, which also supports the use of unilateral jump tests for the assessment of inter-limb asymmetry in lower-limb power. Furthermore, unilateral landing was often associated with the common mechanism of non-contact injuries such as the ACL tear (Heil, Loffing, & Büsch, 2020).

Lower-limb muscle flexibility has been commonly evaluated using the range of motion of lower limb joints (ankle, knee, and hip). A greater range of motion of the joint indicates better flexibility of related muscles (Witvrouw et al., 2003). The Inter-limb asymmetry in muscle flexibility has been assessed by quantifying the difference in range of motion of the joint between the two sides. Although using the same parameter (range of motion), inter-limb asymmetries in flexibility have been assessed in different joints including the ankle (Fousekis et al., 2011; Fousekis et al., 2012; Knapik et al., 1991), knee (Fousekis et al., 2012; Knapik et al., 1991), and hip (Knapik et al., 1991), and findings may vary across the joints. More studies are needed to examine the relationship between inter-limb asymmetry in lower-limb muscle flexibility and sport injury, due to the limited number of studies in the literature.

Inter-limb asymmetry in dynamic balance has been commonly assessed with the SEBT and Y Balance Test. However, there is a lack of a standardized protocol outlining the operation of the SEBT (Coughlan et al., 2012). The variation across protocols includes whether the reaching foot touching floor is allowed, how much movement the standing foot is allowed, and the specific position of the standing foot (Plisky et al., 2009); all of these variations may affect the findings. Therefore, there is a need to develop a standardized protocol for SEBT to allow accurate comparison across studies. Although the Y Balance Test has been developed to improve the standardization of the SEBT with the use of a device composed of three pieces of pipes extending in the anterior, posteromedial, and posterolateral directions (Plisky et al., 2009), some of the problems (e.g., how much movement the standing foot is allowed) still exist.

3.4.2 Participant characteristics

Participants with different characteristics have been included. First, sex may be an important factor affecting the risk of sport injury. A systematic review focusing on child and adolescent sport has reported that boys are generally at greater risk of sport injury compared with girls (Emery, 2003). However, girls showed greater risk of sport injury compared to boys in specific sports including soccer, basketball, and baseball, which might be related to the physiological and anatomical characteristics of girls (Emery, 2003). Moreover, studies have demonstrated a higher rate of specific injuries like ACL ruptures in females compared to males (Agel, Arendt, & Bershadsky, 2005; Dick, Putukian, Agel, Evans, & Marshall, 2007). Although findings are not consistent, it is clear that the potential effects of sex on injury risk should be a consideration when evaluating the association between inter-limb asymmetry in lower-limb functional performance and sport injury. The relationship between inter-limb asymmetry in lower-limb functional performance and sport injury has been examined in both male and female athletes; however, few studies have addressed the difference between sexes in this relationship. Only one study has reported that >10% inter-limb asymmetry in single-leg hop distance indicates greater risk of sport injury in females but not in males (Brumitt et al., 2013), which implies the importance of sex difference when predicting sport injury using inter-limb asymmetry in jump performance.

Athletes from a wide range of sports have been included in studies. However, whether the relationship between inter-limb asymmetry and sport injury can be affected by the difference between sports has not been investigated. Further, there is a lack of studies focusing on laterally dominant sports such as fencing. It is not clear whether or not the inter-limb asymmetry in laterally dominant sports is formed to meet physical demands of these sports and as such be important for injury prevention. For example, Gray, Aginsky, Derman, Vaughan, and Hodges (2016) has reported that the side-to-side asymmetry in the abdominal muscles in cricket fast bowlers is likely adaptations required to perform specific tasks in this sport, and it may not always be detrimental to athletes.

Exposure time and previous injury of the participants may also influence the findings. Greater volume of exposure to sport has been associated with increased risk of injury (Emery & Tyreman, 2009; Emery, 2003; Michaud, Renaud, & Narring, 2001). Athletes with previous injury showed greater risk of injury in sport (Emery & Tyreman, 2009). However, most injury prediction models failed to control the potential influence of these two factors. We recommend including the exposure time to sport and previous injury as covariates when examining the association between inter-limb asymmetry and sport injury.

Risk of sport injury has been reported increasing with age in pediatric-age athletes (Bijur et al., 1995; Emery, 2003; Michaud et al., 2001), which may influence the findings generated from pediatric-age athletes. Only four studies have focused on pediatric-age athletes regarding the association between inter-limb asymmetry in lower-limb functional performance and sport injury. Three studies examined the association between inter-limb asymmetry in lower-limb strength/power and sport injury (Fort-Vanmeerhaeghe et al., 2020; Read et al., 2018; Steidl-Muller et al., 2018); one study examined the association between inter-limb asymmetry in dynamic balance and sport injury (Read et al., 2020). Among these four studies, only one has addressed the effects of growth and maturation on this relationship (inter-limb asymmetry and injury), reporting a difference between growth stages (pre-PHV vs. circa-PHV vs. post-PHV) in the validity of using inter-limb asymmetry in dynamic balance to predict non-contact lower-limb injury (Read et al., 2020). It is expected that more studies can focus on pediatric-age athletes, and further examine the effects of age (or the progress of growth and maturation) on the relationship between inter-limb asymmetry and sport injury.

3.4.3 Definition of injury

Injury had been defined differently across studies. The differences in mechanism (contact vs. non-contact), duration of time loss, and included locations of injury may contribute to the inconsistency of findings. Although contact injuries account for the majority of sport injuries (Bastos, Vanderlei, Vanderlei, Júnior, & Pastre, 2013; Hootman, Dick, & Agel, 2007), some non-contact injuries (e.g., ligament sprains and muscle strains) are the most common sport injuries (Emery, Meeuwisse, & McAllister, 2006; Hootman et al., 2007). Further, non-contact injuries are often associated with modifiable risk factors including neuromuscular disorders such as asymmetries in limb power and postural control (Gonell et al., 2015). Therefore, more studies are expected to focus on the relationship between inter-limb asymmetry and non-contact injury. Regarding the duration of time loss, most studies have included injuries leading to time loss of one day or longer, while there is no uniform requirement of duration. Moreover, time loss was not always a requirement of injury in previous studies. Concerning the location of injury, we recommend associating inter-limb asymmetries (in lower-limb strength/power, dynamic balance, lower-limb muscle flexibility) to injury occurred to lower limbs, since these tests mainly examine physical capacity of the lower extremities.

In addition, the duration of follow-up (for collecting injury) varies across studies, which may also influence the findings. In some studies, participants were prospectively traced for injury for one or two seasons; however, the specific duration of a season was not clearly defined. Future studies should clearly define the duration of follow-up.

3.4.4 Calculation of asymmetries

A variety of equations have been employed to calculate inter-limb asymmetries in lower-limb strength/power, which may contribute to the inconsistency of findings. The variety of equations makes it difficult to compare the given values of inter-limb asymmetry in a test. For example, the widely suggested cut-off value, 15% inter-limb asymmetry in strength/power, may not represent the same amount of asymmetry in studies using different equations to calculate asymmetry, due to the fact that different equations may result in different amounts of asymmetries. Therefore, it is important to pay attention to the equation used for calculating inter-limb asymmetry when utilizing the reported cut-off value for injury prediction.

Regarding the dynamic balance test, most studies have quantified inter-limb asymmetries using the absolute reach distances (cm) measured in the SEBT and Y Balance Test. This may also contribute to the inconsistency of findings due to the influence of leg length. Research has reported that the reach distances in SEBT are correlated with leg length, and a greater leg length is associated with farther reach distance (Gribble & Hertel, 2003). Especially, when using the cut-off value (e.g., 4 cm inter-limb asymmetry) to predict injury, the influence of leg length should be a consideration. Gribble and Hertel (2003) suggested that the reach distance measured in the SEBT and Y Balance Test should be normalized to leg length (leg length%) to ensure the accuracy of comparison between participants or studies. We recommend future research include both the absolute and normalized (to leg length) asymmetry when examining the relationship between inter-limb asymmetry in dynamic balance (measured with the SEBT and Y Balance Test) and sport injury.

In addition, the amount of inter-limb asymmetry may change during the follow-up, which may also influence the results. Longitudinal data are needed to monitor the change in the amount of inter-limb asymmetry during the follow-up. Moreover, the amount of inter-limb asymmetry has been reported with a variable nature and the standard deviation is usually close to or even greater than the mean (Bishop, McCauley, et al., 2019). Research has suggested that the inter-limb asymmetry should be greater than the intra-limb variation (quantified using the coefficient of variation) to make it effective (Turner et al., 2015). In the literature, the ICC is usually reported to evaluate the reliability of data for each leg before calculating the inter-limb asymmetry (Fort-Vanmeerhaeghe et al., 2020; Plisky et al., 2006).

3.5 Conclusions and future directions

In summary, findings regarding the association between inter-limb asymmetry in lower-limb functional performance and sport injury are highly inconsistent, which may be attributed to the differences in tests/parameters, participant characteristics (sex, sporting background, exposure time, previous injury, age), definition of injury, and ways of calculating asymmetry. A clear statement on the association between inter-limb asymmetry in lower-limb functional performance and sport injury is difficult. Research has demonstrated that inter-limb asymmetries in lower-limb power, dynamic balance, and lower-limb muscle flexibility could be used for injury prediction, while a number of considerations should be addressed.

Concerning the selection of tests for the assessment of inter-limb asymmetry in lower-limb strength/power, we recommend using unilateral jump tests because the movement closely reflect the real sporting demands. Regarding the assessment of inter-limb asymmetry in dynamic balance, future study needs to develop a standardized protocol for the SEBT and Y Balance Test to allow accurate comparison between studies.

Future study also needs to address the role of sex when examining the association between inter-limb asymmetry in lower-limb functional performance and sport injury, and the potential effects of exposure time to sport and previous injury should be controlled (when possible). More studies are needed to focus on pediatric-age athletes, and the influence of age on this relationship (asymmetry and injury) needs further investigation. In addition, future study needs to examine this relationship (asymmetry and injury) in asymmetrical sports.

Chapter 4: Risk Factors for Non-Contact Lower-limb Injury: A Retrospective Survey in Pediatric-age Athletes

In this Chapter, a retrospective study was conducted to examine the effects of lateral dominance in sports (laterally dominant vs. non-laterally dominant sports) on non-contact lower-limb injury, and to identify risk factors for non-contact lower-limb injury in pediatric-age athletes.

4.1 Introduction

The injury rate is high in children and adolescents participating in sport activities (Emery & Tyreman, 2009; Emery et al., 2006; Michaud et al., 2001; Radelet et al., 2002). Radelet et al. (2002) reported that the injury rate ranged from 1.0 to 2.3 per 100 athlete exposures in 7-13 y old children in community sports. In 12-15 y old students, the injury rate in sport activities was 60.85 injuries/100 students/year (Emery & Tyreman, 2009). Compared to adults, children and adolescents are more vulnerable to sport injuries due to the stage of maturation in growth cartilage and the musculoskeletal system (Cuff et al., 2010; Radelet et al., 2002). Both acute and overuse injuries in growth cartilage may result in permanent alteration of bone and muscle growth, which may have long-term impact such as disability in later life if the injury is not properly treated (Micheli & Klein, 1991; Patel & Nelson, 2000).

A number of survey studies have investigated sport injury and related risk factors in children and adolescents (Bastos et al., 2013; Bijur et al., 1995; Emery & Tyreman, 2009; Emery et al., 2006; Michaud et al., 2001; Radelet et al., 2002), demonstrating that the most common sport injuries occur to the lower limbs, with the ankle and knee the most frequently injured locations (Bastos et al., 2013; Emery & Tyreman, 2009; Emery et al., 2006). Although contact injuries account for the majority of sport injuries (Bastos et al., 2013; Hootman et al., 2007), some non-contact injuries (e.g., ankle sprains and muscle strains) are found to be the most common injuries across sports (Emery et al., 2006; Hootman et al., 2007). Further, non-contact injuries are often associated with modifiable risk factors such as neuromuscular disorders, overtraining, and being unfit (Gonell et al., 2015). However, there is a lack of survey-based research investigating the risk factors for non-contact lower-limb injury in pediatric-age athletes. This is an important cohort to focus research on, especially considering that children as young as 6 years of age (or even younger) engage in competitive sport training (Malina, 2010).

Regardless of the mechanism (contact vs. non-contact) of injury, studies have reported a range of risk factors for sport injury in children and adolescent, including training duration (Bastos et al., 2013), impact (Bastos et al., 2013; Radelet et al., 2002), age (Emery, 2003), sex (Emery, 2003), previous injury (Emery, 2003; Emery et al., 2006), amount of physical activity (Michaud et al., 2001), and stage of maturity (Michaud et al., 2001). To date, there is a lack of research examining the potential effects of lateral dominance in sport (laterally dominant vs. non-laterally dominant sport) on risk of injury in the lower limbs. Laterally dominant sports (or asymmetric sports, e.g., fencing, badminton, and soccer) are characterized by the two sides of the lower limbs frequently performing in different patterns (Guan et al., 2018) or performing movements that are directed towards one side (Grobbelaar, 2003). For example, in the movement of lunge, which is frequently performed in fencing, tennis, and badminton, the dominant leg performs as the leading leg while the non-dominant leg performs as the supporting leg (Guan et al., 2018). This asymmetrical movement may cause lateral dominance and relative adaptions of the dominant leg in the long-term (Guan et al., 2018). In contrast, non-laterally dominant sports (or symmetric sports, e.g., running, swimming) are characterized by both sides of the lower limbs equally involved in the movements, requiring equal mastery of techniques with the dominant and non-dominant leg (Grobbelaar, 2003). Compared with non-laterally dominant sports, long-term training in laterally dominant sports may cause greater inter-limb asymmetry which has been associated with increased risk of lower-limb injury (Ford et al., 2003; Knapik et al., 1991). To date, there is no evidence available in the literature reporting the injury rate between athletes specialized in laterally dominant vs. non-laterally dominant sports. Therefore, it is unknown empirically whether the laterally dominant moving pattern in laterally dominant sports will increase the risk of lower-limb injury.

The purpose of this study was to examine the effects of lateral dominance in sports (laterally dominant vs. non-laterally dominant sports) on non-contact lower-limb injury, and to identify risk factors of non-contact lower-limb injury in pediatric-age athletes. It was hypothesized that lateral dominance in sports (laterally dominant vs. non-laterally dominant sports) is a significant risk factor for non-contact lower-limb injury. It was also hypothesized that pediatric-age athletes specialized in laterally dominant sports will sustain greater risk of non-contact lower-limb injury compared to those specialized in non-laterally dominant sports.

4.2 Method

4.2.1 Participants

Parents and/or legal guardians of pediatric-age athletes training in sport clubs and/or school teams were eligible to participate in the online survey, if the athletes met the following criteria: (1) were between the ages of 6 and 17 y, (2) specialized in only one sport, and (3) maintained regular training in the preceding 12 months. The level of competition of the athletes were not limited. A power analysis was conducted based on previous report (Cuff et al., 2010), and the required sample size is different based on different parameters. Around 500 participants were required to see the significant effect of sex, while 2900 participants were required to see the significant effect of age. Informed consent was received upon completion and submission of the survey. The investigation received approval from, and was executed in exact accordance with, the ethical guidelines set forth by the University of British Columbia's Clinical Research Ethics Board and the Shandong Sport University's Human Ethics Committee for research involving human participants according to the standards established by Declaration of Helsinki.

4.2.2 Questionnaire

The content of the questionnaire was developed based on previous surveys (Cuff et al., 2010; Radelet et al., 2002). The parents and/or legal guardians were asked to answer 10 questions, reporting their child's age (y), sex, sport, dominant leg (right, left leg), length of training (y), training frequency (1, 2, 3, 4, 5 or more sessions/wk), training intensity (low, moderate, high), whether their children suffered any non-contact lower-limb injury (occurred during training or competition) causing time loss for at least one day from participation in sport activities during the preceding 12 months, and the location and type of the injury. The question types included fill-in-the-blank questions (age, sex, sport, length of training), single-choice questions (dominant leg, training frequency, training intensity, presence or absence of injury), and multiple-choice questions (location and type of injury). A day lost due to injury was any day (including the day in which the participant was injured) where the participant was not permitted to or not able to participate in sporting activities in an unrestricted manner (Rauh, Margherita, Rice, Koepsell, &

Rivara, 2000). Participants were not asked about lower-limb injuries that occurred at a time other than during training or competition, or were caused by contact with equipment or another player. If the athlete sustained more than one injury during the preceding 12 months, participants were asked to report all the injuries (Read et al., 2018). Survey development included examination of the validity of the content. The questionnaire was reviewed by a sports medicine researcher, an athletic trainer, a physical education teacher, a sport psychologist, and three professors in the area of Kinesiology. A pilot test was conducted in a taekwondo club before the actual large-scale survey was disseminated.

4.2.3 Procedures

Participant information and the link to an online questionnaire was sent to the coaches. The coaches were contacted and identified by the members of the research team. The coaches were asked to send this information to the parents and/or legal guardians of the athletes who met the inclusion criteria of this study. The parents and/or legal guardians of the athletes completed and submitted the questionnaire online. All responses were anonymous. The survey was available online from June 2019 to June 2020.

4.2.4 Data analyses

The criterion variable, non-contact lower-limb injury, was analyzed as a categorical variable (presence or absence of injury). Presence of injury was defined as a positive response to the question: "During the preceding 12 months, did you suffer any non-contact lower-limb injury causing time loss for at least one day from participation in sport activities?" The predictor variables are age (y), sex (female vs. male), leg preference (left vs. right leg), sport category (laterally dominant vs. non-laterally dominant sport), length of training (y), training frequency (sessions/wk), and training intensity (low, moderate, high). The continuous measurements (age and length of training) were described as mean ± standard deviation. The other measurements were described with frequencies and percentages.

4.2.5 Statistical analyses

Normality and homoscedasticity assumption of the continuous data (age and length of training) were examined using the Kolmogorov-Smirnov and Levene's test, respectively. Mann Whitney U test was conducted to compare age and length of training between the injured and non-injured athletes as data were not normally distributed. Chi-square tests were employed to compare the proportion of injured athletes based on sex (males, females), training intensity (low, moderate, high intensity), training frequency (1, 2, 3, 4, 5 or more times/wk), leg preference (right, left leg), and sport category (non-laterally, laterally dominant sports).

A multivariate logistic regression model was then used to calculate the adjusted odds ratio (OR) and 95% confidence interval (CI) for each predictor variable. Participants with missing data were excluded from related analyses. All statistical analyses were conducted using SPSS 23 with alpha level set *a priori* at 0.05.

4.3 Results

A total of 2294 questionnaires were submitted. Any response was excluded if there was no response for the question of presence or absence of injury. Data from 2269 questionnaires were included into the final analyses. From these responses, 750 athletes (33.1%) specialized in laterally dominant sports (tennis [101], table tennis [54], soccer [477], badminton [52], fencing [40], long jump [12], shot put [1], high jump [3], baseball [2], and softball [3], skateboard [2], golf [3]), and 1519 athletes (66.9%) specialized in non-laterally dominant sports (swimming [82], running [366], cycling [16], skating [5], basketball [405], taekwondo [330], rope skipping [128], dance [66], hockey [6], volleyball [58], traditional martial art [17], judo [4], kickboxing [20], karate [3], roller skating [10], gymnastics [1], and boxing [2]). A total of 576 (25.4%) athletes sustained non-contact lower-limb injury causing time loss (≥1 d) from participation in sport activities during the preceding 12 months. The ankle (12.1%), thigh (10.8%), and knee (10.6%) were most commonly reported as location of injury (Figure 4.1). Ligament sprain (15.7%) and muscle strain (8.5%) were the most commonly reported non-contact lower-limb injuries (Figure 4.2).

Figure 4.1 Injury breakdown by location

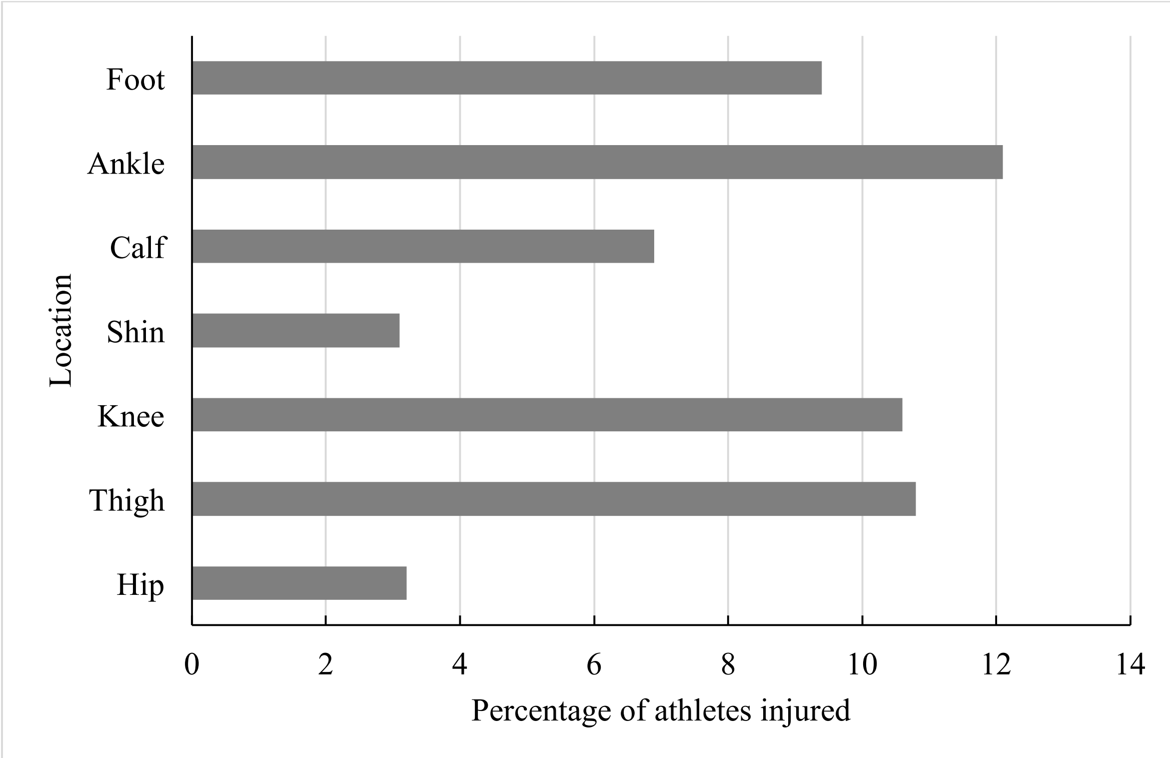
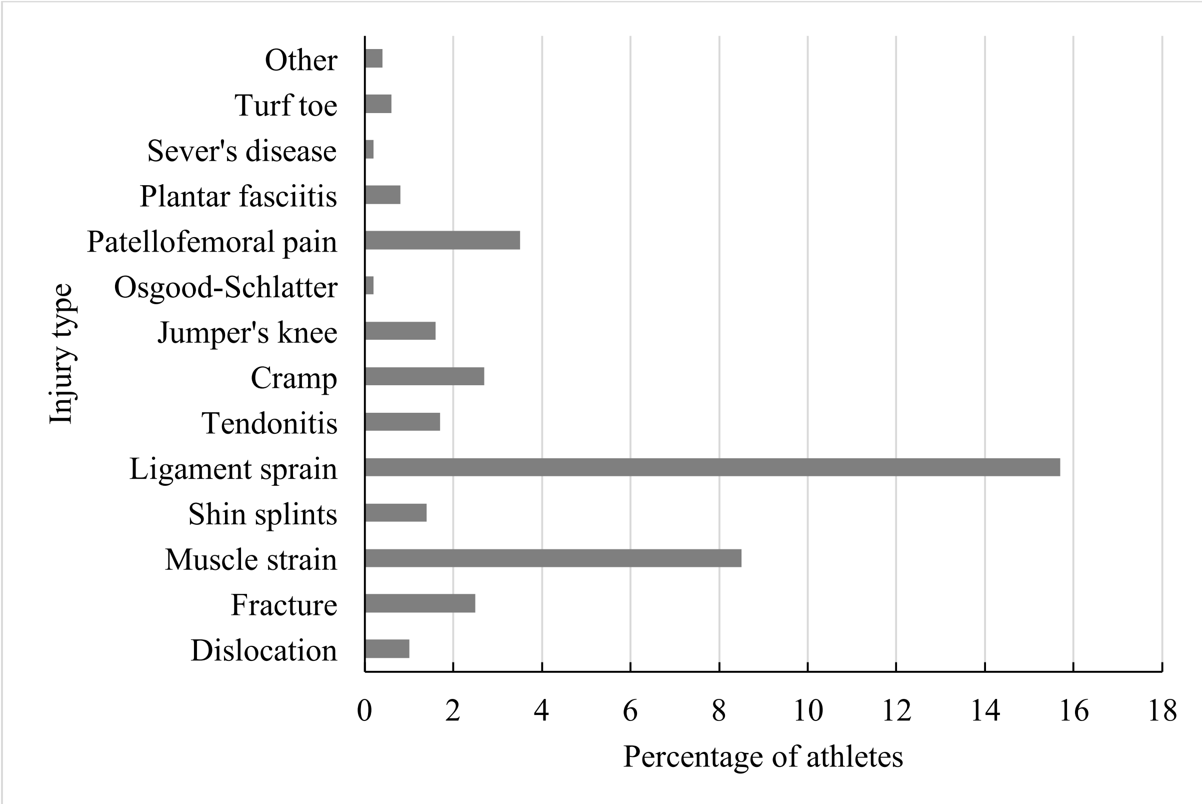


Figure 4.2 Injury breakdown by type



The injured group showed significantly greater age (mean rank: 1417.58 vs. 1009.82, n = 2227, p = 0.000) and length of training (mean rank: 1192.72 vs. 971.22, n = 2059, p = 0.000) compared to the non-injured participants (Table 4.1). Results of the chi-square tests (Table 4.2) showed that the injury rate increased with increasing training intensity (χ^2 [2, 2265] = 151.794, p = 0.000, Cramér's V = 0.259) and training frequency (χ^2 [4, 2267] = 183.817, p = 0.000, Cramér's V = 0.285); the injury rate in laterally dominant sports was significantly greater compared to the non-laterally dominant sports (χ^2 [1, 2269] = 15.673, p = 0.000, Cramér's V = 0.083).

Table 4.1 Mann Whitney U tests for Comparison of age and length of training between non-injured and injured pediatric-age athletes

Variable	Non-injured (mean rank)	Injured (mean rank)	*P*
Age (n = 2227)	1009.82	1417.58	0.000
Length of training (n = 2059)	971.22	1192.71	0.000

Table 4.2 Chi-Square tests comparing the proportion of non-injured vs. injured pediatric-age athletes for each predictor variable

Variable	Non-injured		Injured		χ^2	*P*	Cramér's V
	n	percentage	n	percentage			
Sex							
Female	527	74.5%	180	25.5%	0.003	0.957	0.001
Male	1166	74.6%	396	25.4%			
Leg preference							
Right	1438	75.1%	477	24.9%	1.131	0.288	0.022
Left	249	72.4%	95	27.6%			
Training intensity							
Low	523	83.5%	103	16.5%	151.794	0.000	0.259
Moderate	1090	75.4%	355	24.6%			
High	77	39.7%	117	60.3%			
Training frequency							
1 time/wk	678	84.4%	125	15.6%	183.817	0.000	0.285
2 times/wk	620	80.5%	150	19.5%			
3 times/wk	191	63.2%	111	36.8%			
4 times/wk	78	53.1%	69	46.9%			
≥5 times/wk	125	51%	120	49%			
Sport category							
LD sport	521	69.5%	229	30.5%	15.673	0.000	0.083
NLD sport	1172	77.2%	347	22.8%			

LD, laterally dominant sport; NLD, non-laterally dominant sport.

Table 4.3 Multivariate logistic regression analysis for predicting non-contact lower-limb injury in pediatric-age athletes

Variable	Adjusted OR (95% CI)	*P*
Age (y)	1.21 (1.16-1.26)	0.000
Length of training (y)	1.03 (0.96-1.11)	0.396
Training intensity	1.77 (1.43-2.19)	0.000
Training frequency (sessions/wk)	1.36 (1.25-1.48)	0.000
Sex		
Female vs. Male	0.88 (0.70-1.12)	0.310
Sport category		
LD vs. NLD sport	1.38 (1.10-1.75)	0.006
Leg preference		
Right vs. Left leg	0.71 (0.53-0.95)	0.023

LD, laterally dominant; NLD, non-laterally dominant; OR, odds ratio; CI, confidence interval.

In the multivariate logistic regression model (Table 4.3), risk of non-contact lower-limb injury increased with increasing age (adjusted OR, 1.21 for increase of 1 year old; 95% CI, 1.16-1.26; $p = 0.000$), training intensity (adjusted OR, 1.77 for increase of 1 level; 95% CI, 1.43-2.19; $p = 0.000$), and training frequency (adjusted OR, 1.36 for increase of 1 training day per week; 95% CI, 1.25-1.48; $p = 0.000$). Athletes specialized in laterally dominant sports showed greater risk of non-contact lower-limb injury compared to those specialized in non-laterally dominant sports (adjusted OR, 1.38; 95% CI, 1.10-1.75; $p = 0.006$). Right-leg preference indicated lower risk of non-contact lower-limb injury compared to left-leg preference (adjusted OR, 0.71; 95% CI, 0.53-0.95; $p = 0.023$).

4.4 Discussion

4.4.1 Injury analyses

This is the first survey study to our knowledge focusing on non-contact lower-limb injury in pediatric-age athletes. Our results showed that 25.4% of the athletes in our respondent sample sustained non-contact lower-limb injury (≥1-d time loss from sport activities) in a 12-month period. It is difficult to make age-matched comparisons between our results and previous findings because of the lack of research focusing on non-contact lower-limb injury in children and adolescents. Brumitt et al. (2019) reported the same injury rate (25.4%) when examining non-contact lower-back and lower-limb injury (≥1-d time loss from sport activities) in 169 male collegiate basketball players in one season. However, the rate of non-contact lower-limb injury varies greatly in other studies: Stiffler et al. (2017) reported that 19.4% of 147 collegiate athletes sustained non-contact injuries in the knee or ankle in one academic year; while, Izovska et al. (2019) reported that 33.6% of 227 professional soccer athletes sustained non-contact lower-limb injuries in one season. This range in injury rate may be influenced by the definition of injury used in the research and differences in participant characteristics across studies.

Our results showed that ligament sprain (15.7%) and muscle strain (8.5%) were the most frequently occurred injuries. This result is consistent with previous findings generated from 9-12th grade students (Cuff et al., 2010) and 12-15 y old students (Emery et al., 2006) in sport activities. Further, our results showed that ankle (12.1%), thigh (10.8%), and knee (10.6%) were the most frequently injured locations. Similarly, ankle and knee were also reported as the most frequently injured locations in adolescent (aged 14.67 ± 2.08 y) soccer players during training and competition (Bastos et al., 2013), 5-17 y old children and adolescents in sport activities (Bijur et al., 1995), and 12-15 y old students in sport activities (Emery et al., 2006). The high rate of injury in these locations may be related to the anatomy of the knee and ankle (Tham, Tsou, & Chee, 2008), and the imbalance in force absorption of the quadriceps and hamstrings in sport activities (Read, Oliver, Croix, Myer, & Lloyd, 2016). The preponderance of injuries to the ankle and knee implies particular emphasis in injury prevention and sport training education in this area.

4.4.2 Effects of lateral dominance in sport on non-contact lower-limb injury

This is the first study to compare the rate of sport injury in athletes specialized in laterally dominant vs. non-laterally dominant sports. Results of the chi-square test showed that the rate of non-contact lower-limb injury was significantly greater in athletes specialized in laterally dominant sports (30.5%) vs. non-laterally dominant sports (22.8%). The multivariate logistic regression model showed supportive results, wherein athletes specialized in laterally dominant sports were 1.38 times more likely to sustain non-contact lower-limb injury compared to athletes specialized in non-laterally dominant sports after controlling for the effects of other factors. Cumulatively, these results suggest that pediatric-age athletes specialized in laterally dominant sports may need close monitoring for non-contact lower-limb injury by the coaches, athletic trainers, medical staff, and parents. We speculate that the long-term use of a laterally dominant moving pattern may result in greater inter-limb asymmetry in athletes specialized in laterally dominant sports, leading to greater odds of non-contact lower-limb injury. Future research is warranted to examine this postulation further.

To date, there is a lack of research in terms of classifying laterally dominant and non-laterally dominant sports in the literature. The present study suggests a way to classify laterally dominant and non-laterally dominant sports on the basis of the pattern of movement in the lower extremities in a sport. Sport which requires large amount of movement characterized by the two sides performing/functioning differently was classified as a laterally dominant (or asymmetric) sport in the present study. For example, in the lunge, which is frequently performed in fencing, tennis, and badminton, the dominant leg performs as the leading leg and the non-dominant leg performs as the supporting leg (Guan et al., 2018). In contrast, a non-laterally dominant (or symmetric) sport was classified as a sport where both legs are expected to be equally involved, such as running, swimming, and cycling (Grobbelaar, 2003). In addition, a sport which requires a large amount of single-leg jumps (e.g., basketball and volleyball) or single-leg support/drive (e.g., kickboxing, taekwondo) on both sides was also classified as a non-laterally dominant (or symmetric) sport in the present study, despite the fact that the dominant leg is usually more involved than the non-dominant leg in practical action (Grobbelaar, 2003). The method suggested in the present study could be used by future research with a need to classify laterally dominant and non-laterally dominant sports.

4.4.3 Other risk factors for non-contact lower-limb injury

Our results indicate that the risk of non-contact lower-limb injury increases with age in pediatric-age athletes. A number of studies have demonstrated similar findings. Cuff et al. (2010) reported that the risk of overuse injuries increased with age in 9-12th grade students. Bijur et al. (1995) reported that the rate of sport injury increased with age in 5-17 y old children. In addition, Michaud et al. (2001) reported that the rate of sport injury increased with age in 9-16 y old students. The heightened risk of sport injury with increasing age may stem from the increased level of competition and time participating in sport as a function of age (Emery, 2003). Taken together, these findings suggest that pediatric-age athletes may need close monitoring for injury, especially as they get older. However, findings in the literature are not always consistent. Some studies demonstrated that age was not associated with the risk of sport injury in junior high school students aged between 12 and 15 y (Emery & Tyreman, 2009), or in adolescent male soccer athletes aged 14.7 ± 2.1 y (Bastos et al., 2013). The inconsistency of findings may be attributed to differences in age stages and definition of injury across studies. We suggest future studies include participants with a wide range of ages (e.g., from 6 to 17 y) when evaluating the relationship between age and sport injury in pediatric-age athletes.

Currently, there is a lack of research concerning the effects of training frequency and intensity on sport injury. Our results indicate that the risk of non-contact lower-limb injury increased with increasing training frequency (1, 2, 3, 4, 5 or more times/wk) in pediatric-age athletes. An increase of 1 training session per week increased the risk of non-contact lower-limb injury by 1.36 times. This finding suggests that coaches in youth sport training may need to reduce training frequency to prevent injury in pediatric-age athletes when required, although the effects of training duration in one training session has not been considered in the present study. Another consideration is that the training frequency of athletes who play on multiple teams (for the same sport) may not be scheduled by one coach. It is recommended that pediatric-age athletes play on only one team at a time to help decrease training frequency and the risk of injury. Our results also indicate that an increase of 1 level (low, moderate, high) in training intensity increases the odds of non-contact lower-limb injury by 1.77 times when controlling for the effects of other factors. It should be noted that there was no clear boundary of each intensity level (low, moderate, high) in the present study, and the training intensity was self-evaluated by the participants, which may have led to the under reporting of injury cases. Nevertheless, the present study provides a preliminary evidence on the effects of training frequency and intensity on non-contact lower-limb injury in pediatric-age athletes.

With respect to the effects of length of training on sport injury, results are inconclusive in the present study. Although the injured group showed greater length of training than the non-injured group, results of the multivariate logistic regression model showed no association between length of training and non-contact lower-limb injury after controlling for the effects of other factors. Available evidence on the influence of length of training on sport injury is scarce. Bastos et al. (2013) reported that male soccer athletes (14.7 ± 2.1 y) with a training duration greater than 5 years sustained sport injury more frequently compared to those with a shorter training duration. The greater length of training demonstrates greater exposure time to training and competition, which may contribute to greater risk of injury (Stege, Stubbe, Verhagen, & Van Mechelen, 2011). Further, with the increase of length of training, games may become more competitive, which may also increase the risk of injury (Brito et al., 2011).

Regarding the effects of sex (male vs. female) on risk of sport injury, a systematic review focusing on children and adolescent has reported that boys are generally at greater risk of sport injury compared with girls because of the larger body mass, which may cause increased forces in jumping, sprinting, and pivoting in boys (Emery, 2003). However, girls showed greater risk of sport injury compared with boys in specific sports including soccer, basketball, and baseball, which may be related to the physiological and anatomical characteristics of girls (Emery, 2003). Focusing on non-contact lower-limb injury, our results showed that there was no difference in risk of injury between boys and girls. This might be attributed to the variance of sporting background of the participants in the present study. Overall, practitioners should pay attention to the differences between sports and consider the potential effects of sex (male vs. female) on the risk of injury in pediatric-age athletes.

Another finding is that left-leg preference indicates greater risk of non-contact lower-limb injury compared to right-leg preference, suggesting that pediatric-age athletes with left-leg preference may need close monitoring for non-contact lower-limb injury. This finding is consistent with previous research examining risk factors for injury in 12-18 y old (Emery, Meeuwisse, & Hartmann, 2005) and 7-12 y old soccer athletes (Rössler et al., 2018). Reasons for these findings are unclear. It has been suggested that these findings may be associated with the environmental biases in a right-handed world and differences in functional related to neurologic development (Graham & Cleveland, 1995). This is an area for further research.

4.4.4 Limitations

We acknowledge the limitations in the present study. Non-contact lower-limb injuries were self-reported by parents/guardians in the present study, which may lead to under-reporting of injury cases. It may also cause recall bias as the parents need to remember events up to 12 months before, as well as classify injuries by themselves instead of medically trained staff. Moreover, the parents and/or guardians whose children had sport injury before may have more interest in participating in the present survey, which may cause recruitment bias. In addition, although we tried to include all injuries, we were not able to record repetitive injuries in the same part of the body due to the design of the questionnaire. Further, it has been suggested that the effects of previous injury (Emery & Tyreman, 2009; Emery et al., 2006) and exposure time to sports (Michaud et al., 2001; Taunton et al., 2003) should be considered when evaluating injury risk;

however, these two factors were not included in the present study. Therefore, our findings did not take into account the effects of exposure time and previous injury.

4.5 Conclusion

Pediatric-age athletes who specialize in laterally dominant sports may demonstrate greater risk of non-contact lower-limb injury compared to those specialized in non-laterally dominant sports. Left-leg preference, increase in age, training intensity, and training frequency were also associated with greater risk of non-contact lower-limb injury in pediatric-age athletes. These findings should be utilized with caution as exposure time and previous injury were not included. However, this study provides useful findings in evaluating the risk of non-contact lower-limb injury in pediatric-age athletes, and the effects of lateral dominance in sport (laterally vs. non-laterally dominant sport) on injury. Future research should include more comprehensive predictor variables to further examine risk factors of non-contact lower-limb injury in pediatric-age athletes. Future research should also explore whether the greater odds of non-contact lower-limb injury in pediatric-age athletes specialized in laterally dominant vs. non-laterally dominant sports is a result of greater inter-limb asymmetry.

Chapter 5: Bilateral Difference Between Lower Limbs in Children Practicing Laterally Dominant vs. Non-Laterally Dominant Sports

The purpose of this chapter was to examine inter-limb asymmetry in lower-limb functional performance in child athletes specialized in laterally dominant vs. non-laterally dominant sports. To accomplish this purpose, inter-limb asymmetries in performance of unilateral jumps and the Star Excursion Balance Test in 9-11 y old fencers (laterally dominant sport) and taekwondo athletes (non-laterally dominant sport) were examined and compared.

5.1 Introduction

The topic of inter-limb asymmetry (or bilateral asymmetry, bilateral difference) in lower-limb functional performance has received growing attention because of the association with the risk of sport injury (Knapik et al., 1991; Plisky et al., 2006). Inter-limb asymmetry may potentially place both legs at an increased risk of injury (Ford et al., 2003). The strong leg may sustain exceptionally high force because of increased dependence and high loading on that side, whereas it may be difficult for the weak leg to endure even average force in sport activities (Ford et al., 2003).

The inter-limb asymmetry in lower extremities has been reported in a wide range of sports including both laterally (Nyström et al., 1990; Tsolakis & Tsiganos, 2008) and non-laterally (Pappas et al., 2015) dominant sports. Laterally dominant sports (e.g., fencing, badminton) are characterized by the two sides of the legs frequently performing different patterns (Guan et al., 2018). In contrast, non-laterally dominant sports (e.g., running, taekwondo) are characterized by both sides of the body equally involved in the movements, requiring equal mastery of techniques with the dominant and non-dominant leg (Grobbelaar, 2003). While inter-limb asymmetry is common in both laterally and non-laterally dominant sports, there is a lack of research comparing the amount of inter-limb asymmetry in athletes specialized in laterally vs. non-laterally dominant sports, revealing a gap in the literature. Comparing inter-limb asymmetries reported across studies is also difficult, due to the variety in assessments and ways of calculating inter-limb asymmetry. Therefore, it is important to design research that examines the effects of lateral dominance (laterally vs. non-laterally dominant sport) on inter-limb asymmetry by including both laterally dominant and non-laterally dominant sports.

The difference between female and male athletes in inter-limb asymmetry in leg strength/power has been observed. Female soccer athletes have shown inter-limb asymmetry in isometric strength of the hip abductors versus no inter-limb asymmetry in male soccer athletes (Brophy et al., 2009). Similar findings have been reported when examining the isometric strength of legs in National Collegiate Athletic Association athletes (Owens et al., 2011). Additionally, female team players showed greater bilateral difference in single-leg jump performance compared with males (Bampouras & Dewhurst, 2018). However, in research examining the inter-limb asymmetry in dynamic balance, female high-school athletes demonstrated less amount of inter-limb asymmetry compared to their male counterparts (Gorman et al., 2012; Miller et al., 2017).

In comparison to adults, child athletes are more vulnerable to sport injuries as the growth cartilage throughout the immature musculoskeletal system is more susceptible to injury (Cuff et al., 2010; Radelet et al., 2002). Research has reported that the injury rate ranged from 1.0 to 2.3 per 100 athlete exposures in 7-13 year old children in community sports (Radelet et al., 2002).

To explore the influence of inter-limb asymmetry in lower-limb functional performance on risk of sport injury in children, it is important to examine the profile of inter-limb asymmetry in children and the factors impacting on it. Therefore, the main purpose of the present investigation was to examine bilateral differences in unilateral jump performance and dynamic balance in 9-11 y old boys and girls specialized in laterally dominant (fencing) vs. non-laterally dominant sports (taekwondo). It was hypothesized that children specialized in fencing and taekwondo will show inter-limb asymmetries in unilateral jump performance and dynamic balance, and there may be an difference between sexes. It was further hypothesized that specializing in laterally dominant sports will be associated with greater amount of inter-limb asymmetry.

5.2 Methods

5.2.1 Participants

A power analysis was conducted before participant recruitment, and the results showed that 17 participants were required for each sport within each sex. A total of 28 fencers (19 boys and 9 girls, aged 9.7 ± 1.1 y) were recruited into the laterally dominant sport group, and then 28 age- and maturity-matched taekwondo athletes (19 boys and 9 girls, aged 9.7 ± 1.1 y) were recruited into the non-laterally dominant sport group. All participants were between 9-11 y old. Maturity was first determined from predicting years from peak height velocity (a maturity offset value) by using anthropometric variables (Mirwald, Baxter-Jones, Bailey, & Beunen, 2002). All participants had at least one year of training experience and maintained regular training in the preceding 12 months before participation. All participants specialized at one sport (fencing or taekwondo). The investigation received approval from, and was executed in exact accordance with, the ethical guidelines set forth by the University of British Columbia's Clinical Research

Ethics Board and the Shandong Sport University's Human Ethics Committee for research involving human participants according to the standards established by Declaration of Helsinki. Written informed consent was received from parents/guardians of participants, and written informed assent was obtained from participants.

5.2.2 Assessments of inter-limb asymmetry

Jump tests included the single-leg CMJ, hop, and triple hop tests. The unilateral jump tests have been shown to be valid and reliable (ICC = 0.81-0.99) for assessing the inter-limb asymmetry in lower-limb power (Bishop et al., 2021). Dynamic balance was measured using the SEBT which is a valid (coefficient of variation = 2.82-5.42%) and reliable (ICC = 0.78-0.96) (Hertel, Miller, & Denegar, 2000) test developed by Gray (1995).

Single-leg CMJ. The goal of this test was to obtain the maximum jump height of each leg after performing a single-leg countermovement. Participants stood in an upright position with feet positioned shoulder width apart and hands on hips (to reduce the impact of arm movement) (Impellizzeri et al., 2007). To start the test, one leg was lifted off the ground to a self-selected position, then the participant performed a countermovement to a comfortable depth followed by a vertical jump. Participants were instructed to jump as high as possible with hands on hips during the entire movement. The entire movement was recorded with an iPhone 6s (Apple, Inc., USA) at 240 Hz. The jump height was calculated based on the flight time of the jump by identifying the take-off and landing frames using the "My Jump" iPhone application, which has been reported a valid and reliable method (Haynes et al., 2019). Three valid trials were required for each leg. The jump height in each trial was recorded, and the average jump height of the three trials in each leg was used for analysis.

Single-leg hop. The goal of this test was to obtain the maximum horizontal distance of a hop. Participants started by standing with one leg and toes behind the starting line. Participants were then instructed to hop forward as far as possible and land firmly with the same leg. Failure to perform a firm landing was viewed as an invalid trial. The hop distance from the starting line to the participant's landing heel was measured and recorded. Three valid trials were required for each leg. The average distance of the three trials of each leg was used for analysis.

Single-leg triple hop. The goal of this test was to obtain the total horizontal distance of three consecutive hops. Participants started by standing with one leg and toes behind the starting line. Participants were then instructed to perform three consecutive forward hops as far as possible using the same leg, with the intention of reducing the floor contact time of the first two landings as much as possible. The landing of the last hop had to be firm. Failure to perform a firm landing at the last hop was viewed as an invalid trial. The total hop distance from the starting line to the participant's final landing heel was measured and recorded. Three valid trials were required for each leg. The average distance of the three trials of each leg was used for analysis.

Star Excursion Balance Test (SEBT). The SEBT was applied to assess dynamic balance in three directions: anterior, posteromedial, and posterolateral. The goal of this test was to obtain the maximum reaching distance along the three directions using the contralateral limb while maintaining a unilateral stance with solid foundation. While standing with a single leg at the convergence of reach direction lines, the participants were instructed to reach as far as possible with the other leg along each of the three directions (in the order of anterior, posteromedial, and posterolateral direction), lightly touching each line using the most distal part of the reaching foot without disrupting the established balance during the entire movement. The point where the most distal part of the foot reached was marked with erasable ink on each direction line. Each participant performed three trials using each leg. Participants took this test barefoot to eliminate the effects of shoes on balance and stability. The trial was viewed as invalid when participants failed to maintain the unilateral stance, move or lifted the standing foot from the convergence of lines, or failed to return the reaching foot to the original position (Plisky et al., 2006). The greatest reach distance from the convergence of lines to the point where the most distal part of the foot reached of the three trials for each direction of each leg was measured and used for analysis (Plisky et al., 2006).

5.2.3 Procedure

First, participants took anthropometric measurements including height, sitting height, leg length, and body weight. Protocols for anthropometric measurements are reported elsewhere (Buschang, Malina, & Little, 1986; Gribble & Hertel, 2003). Limb dominance was examined by letting the participant kick a soccer ball, and the limb which the participant preferred for the ball kicking was defined as the dominant leg. Participants then completed all assessments of jump tests and dynamic balance in one session. At the start of the session, each participant completed stretching and a five-minute jog to warm-up. Participants were then provided with test instructions and received time to practice until they were familiar with each test. For the SEBT, participants performed at least six practice trials in each direction to account for learning effects (Hertel et al., 2000). Following test familiarization, participants received 5-min of rest. Participants then completed the tests in the following order: single-leg CMJ, hop, triple hop, and SEBT, with a one-minute rest between each test. The starting leg was randomly selected to reduce the order effect.

5.2.4 Data analyses

The reach distance in SEBT was normalized to limb length (limb length%), and the composite reach distance was calculated by averaging the reach distance of the three directions. The magnitude of inter-limb asymmetry for each dependent variable was quantified using an equation modified from previous studies (Sugiyama et al., 2014; Wong et al., 2007): Asymmetry = (Stronger Limb − Weaker limb) × 2 / (Stronger Limb + Weaker limb) × 100%.

5.2.5 Statistical analyses

Descriptive data are shown as mean ± standard deviation. Normal distribution and homoscedasticity assumption of the data were examined using the Kolmogorov-Smirnov and Levene's tests, respectively. A two-way between group ANOVA [2 (Sex: boys, girls) × 2 (Sport group: fencing, taekwondo)] was conducted to examine for difference for participants' characteristics (body weight, height, and maturity offset). A mixed model design ANOVA [2 (Sex: boys, girls) × 2 (Sport group: fencing, taekwondo) × 2 (Limb: dominant, non-dominant leg)] was conducted to examine for difference for each test (jump tests and SEBT). Where significant differences were found between sport groups or sexes, independent *t* tests were performed. For differences found between the dominant and non-dominant legs, paired *t* tests were performed. Effect size reported using Cohen's d was described as small (< 0.5), moderate

(0.51 - 0.79) and large (> 0.8) (Cohen, 1988). To compare the age and length of training between sexes and sport groups, a non-parametric test (Mann Whitney U) was conducted as the distribution was not normal. Statistical significance was set a priori at $p < 0.05$. The amount of inter-limb asymmetry was compared between sport groups in each sex using Mann Whitney U test. All statistical analyses were conducted using SPSS 23.

5.3 Results

5.3.1 Participant characteristics

Descriptive statistics for participant characteristics is shown in Table 5.1. There was a significant main effect of sex for maturity offset ($F_{(1,52)} = 4.594$, $p = 0.037$, $\eta^2 = 0.081$). The girls were significantly further away from their peak height velocity compared to the boys (-3.29 ± 0.99 vs. -2.71 ± 0.89, $p = 0.033$, effect size = 0.629). The length of training was significantly (U = 176.000, $z = -3.719$, $p = 0.000$) greater in the taekwondo group (Mean Rank = 36.21, n = 56) compared to the fencing group (Mean Rank = 20.79, n = 56).

Table 5.1 Participant characteristics (mean ± SD)

Variables	Fencing		Taekwondo	
	Boys (n = 19)	Girls (n = 9)	Boys (n = 19)	Girls (n = 9)
Age (y)	9.58 ± 1.02	10.00 ±1.22	9.58 ± 1.02	10.00 ± 1.22
Maturity offset (y)[a]	-2.67 ± 0.96	-3.27 ± 1.00	-2.75 ± 0.85	-3.31 ± 1.03
Length of training (y)[b]	1.65 ± 0.76	1.44 ± 0.53	3.20 ± 1.37	2.33 ± 1.22
Height (cm)	149.27 ± 10.86	148.92 ± 11.66	148.10 ± 8.74	146.89 ± 13.24
Body weight (kg)	46.83 ± 15.86	43.32 ± 9.46	46.52 ± 14.45	40.08 ± 11.50

[a] Main effect of sex.
[b] Significant difference between the fencing and taekwondo group.

5.3.2 Jump performance

There was a significant limb by sex interaction ($F_{(1,52)} = 15.990$, $p = 0.000$, $\eta^2 = 0.235$) for the single-leg CMJ height (Table 5.2). The jump height of the dominant leg was significantly greater (10.38 ± 2.72 vs. 9.36 ± 2.73, p = 0.000, effect size = 0.841) compared to the non-dominant leg in boys, whereas no significant difference (p = 0.872) was shown in girls (Figure 5.1A).

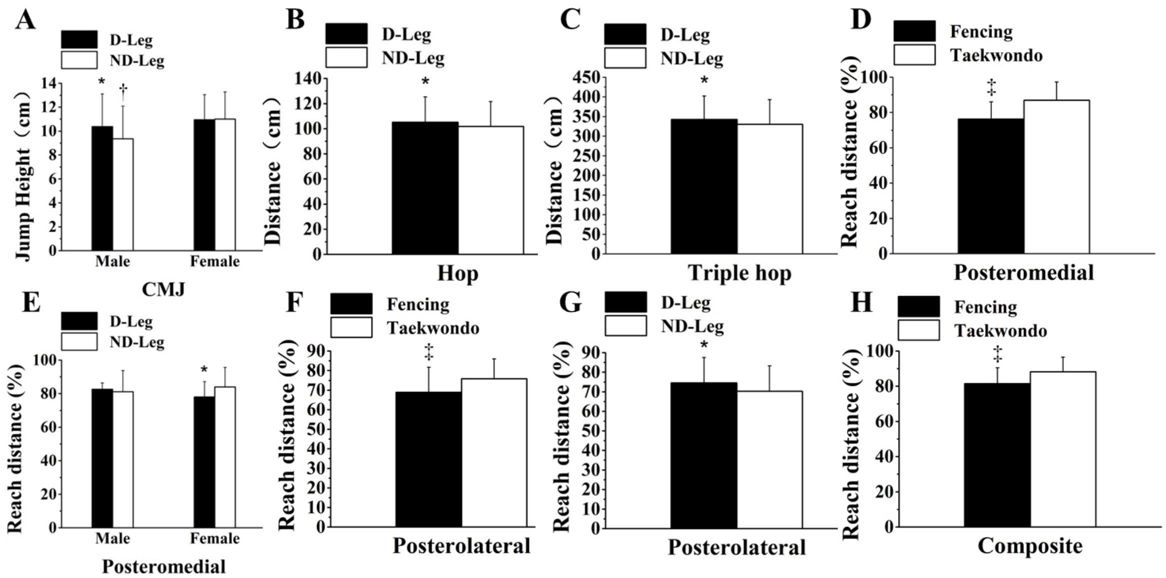
A significant main effect of limb was shown for single-leg hop ($F_{(1,52)}$ = 9.669, p = 0.003, η^2 = 0.157) and triple hop ($F_{(1,52)}$ = 12.908, p = 0.001, η^2 = 0.199) distance (Table 5.2). The performance of the dominant leg was significantly better in both the hop (105.11 ± 20.27 vs. 101.81 ± 19.74, p = 0.001, effect size = 0.449, Figure 5.1B) and triple hop (342.71 ± 59.63 vs. 330.20 ± 62.67, p = 0.000, effect size = 0.567, Figure 5.1C) tests compared to the non-dominant leg.

Table 5.2 Descriptive statistics for single-leg jump and SEBT performance (mean ± SD)

Variable	Limb	Fencing		Taekwondo	
		Boys (n = 19)	**Girls (n = 9)**	**Boys (n = 19)**	**Girls (n = 9)**
CMJ (cm)[a,c]	DL	10.00 ± 2.56	10.14 ± 1.89	10.96 ± 2.73	11.77 ± 2.06
	NDL	8.62 ± 2.69	10.20 ± 2.12	9.91 ± 2.72	11.80 ± 2.23
Hop (cm)[a]	DL	96.00 ± 17.92	105.37 ± 23.56	110.35 ± 20.01	113.06 ± 17.69
	NDL	92.89 ± 19.41	104.30 ± 20.50	106.89 ± 18.66	107.43 ± 18.27
Triple hop (cm)[a]	DL	321.89 ± 60.69	349.48 ± 69.09	354.25 ± 50.52	355.48 ± 63.70
	NDL	298.00 ± 60.00	342.11 ± 70.95	346.89 ± 52.39	351.02 ± 62.62
ANT RD (%)	DL	99.95 ± 8.55	98.88 ± 8.53	102.11 ± 8.05	101.04 ± 9.30
	NDL	99.56 ± 6.73	98.03 ± 7.87	101.74 ± 7.31	102.25 ± 8.75
PM RD (%)[b,c]	DL	76.68 ± 11.65	74.40 ± 9.76	88.49 ± 13.57	81.82 ± 6.74
	NDL	75.75 ± 10.31	78.32 ± 11.03	86.59 ± 12.54	89.75 ± 9.51
PL RD (%)[a,b]	DL	70.96 ± 13.93	73.65 ± 15.10	76.94 ± 13.18	77.88 ± 6.92
	NDL	65.32 ± 14.22	67.62 ± 10.87	73.44 ± 13.74	76.51 ± 5.81
COM RD (%)[b]	DL	82.53 ± 10.54	82.31 ± 9.86	89.18 ± 10.21	86.91 ± 6.03
	NDL	80.21 ± 9.03	81.33 ± 7.84	87.26 ± 10.53	89.51 ± 5.50

CMJ, countermovement jump; DL, dominant leg; NDL, non-dominant leg; ANT, anterior; PM, posteromedial; PL, posterolateral; COM, composite; RD, reach distance; D-Leg, dominant leg; ND-Leg, non-dominant Leg.
[a] Main effect of limb.
[b] Main effect of sport group.
[c] Significant interaction between limb and sex.

Figure 5.1 T tests examining the simple effect



5.3.3 Star Excursion Balance Test (SEBT)

There was a significant main effect of sport group (fencing vs. taekwondo) for posteromedial ($F_{(1,52)} = 12.477$, $p = 0.001$, $\eta^2 = 0.194$), posterolateral ($F_{(1,52)} = 4.115$, $p = 0.048$, $\eta^2 = 0.073$), and the composite ($F_{(1,52)} = 6.828$, $p = 0.012$, $\eta^2 = 0.116$) reach distance (Table 5.2). The taekwondo group showed significantly greater posteromedial (86.98 ± 10.32 vs. 76.26 ± 9.85, $p = 0.000$, effect size = 1.063, Figure 5.1D), posterolateral (75.83 ± 10.21 vs. 68.94 ± 12.75, $p = 0.030$, effect size = 0.597, Figure 5.1F), and composite (88.21 ± 8.33 vs. 81.51 ± 9.04, $p = 0.006$, effect size = 0.771, Figure 5.1H) reach distance (averaged by two sides) compared to the fencing group.

There was a main effect of limb ($F_{(1,52)} = 7.752$, $p = 0.007$, $\eta^2 = 0.130$) for posterolateral reach distance (Table 5.2). The reach distance was significantly greater (74.53 ± 12.99 vs. 70.25 ±

13.02, p = 0.003, effect size = 0.419) when using the dominant leg for support compared with using the non-dominant leg (Figure 5.1G).

There was a significant interaction between limb and sex ($F_{(1,52)}$ = 7.260, p = 0.009, η^2 = 0.123) for posteromedial reach distance (Table 5.2). The posteromedial reach distance in girls was significantly greater (84.04 ± 11.59 vs. 78.11 ± 8.99, p = 0.010, ES = 0.681) when using the non-dominant leg for support compared with using the dominant leg; there was no significant difference (p = 0.376) between the two sides in boys (Figure 5.1E).

5.3.4 Magnitude of asymmetry

The magnitude of asymmetry between lower limbs in each test is shown in Table 5.3. No significant difference was shown between sport groups in each sex.

Table 5.3 Descriptive statistics for asymmetry magnitude in jump performance and dynamic balance tests (mean ± SD)

Asymmetry (%)	Fencing		Taekwondo	
	Boys (n = 19)	Girls (n = 9)	Boys (n = 19)	Girls (n = 9)
CMJ	16.72 ± 12.20	8.47 ± 7.97	13.37 ± 8.95	10.09 ± 6.46
Hop	7.81 ± 6.11	4.90 ± 3.59	5.75 ± 4.14	7.18 ± 6.54
Triple hop	8.82 ± 7.63	2.88 ± 2.57	5.13 ± 4.46	4.02 ± 2.73
ANT RD	3.87 ± 3.22	6.86 ± 5.42	5.24 ± 4.65	3.30 ± 3.97
PM RD	7.91 ± 6.14	9.50 ± 8.50	9.50 ± 9.27	9.35 ± 9.11
PL RD	13.98 ± 10.89	10.59 ± 9.14	11.47 ± 13.25	8.92 ± 5.78
COM RD	4.94 ± 3.56	6.44 ± 3.14	6.90 ± 6.97	4.10 ± 2.71

CMJ, countermovement jump; ANT, anterior; PM, posteromedial; PL, posterolateral; COM, composite; RD, reach distance.

5.4 Discussion

5.4.1 Jump performance

As age and maturity dramatically affect sport performance in children (Armstrong, Barker, & McManus, 2015; Malina et al., 2005), the age and maturity of the participants in the taekwondo group was matched with each participant in the fencing group to eliminate related effects and better reflect the effects caused by lateral dominance in sport (fencing vs. taekwondo). The results showed that there was a main effect of limb for single-leg CMJ, hop, and triple hop performance, and there was no interaction between limbs and sport groups. Moreover, no difference was found in the amount of inter-limb asymmetry between sport groups in each sex. These findings indicate that inter-limb asymmetry in lower-limb power may be caused by leg preference (preferred vs. non-preferred leg) instead of the lateral dominance in sports (laterally vs. non-laterally dominant sport) in 9-11 y old athletes.

By quantifying the amount of inter-limb asymmetry, we found that the most evident magnitude of inter-limb asymmetry in jump tests was 16.72% in single-leg CMJ height in boys of the fencing group. Research has reported that an inter-limb asymmetry above 15% in lower-limb isokinetic strength and jump performance indicates increased risk for sport injury in collegiate and professional athletes (Knapik et al., 1991; Schiltz et al., 2009). However, the external validity of these findings may be limited. The isokinetic assessment of muscle strength used in these studies may not be specific to most of the sport activities which are characterized by fast muscle actions involving stretch-shortening cycle (Impellizzeri et al., 2007). Instead, the functional jump tests are recommended to assess inter-limb asymmetry in lower-limb strength, because of the required stretch-shortening cycle and high-rate force production in these tests

(Impellizzeri et al., 2007). Moreover, it is unclear how to adjust for different sexes when using this threshold (15%), since Knapik et al. (1991) have only included female athletes, and the sex of the participants is not clearly reported by Schiltz et al. (2009). In addition, the equations used for calculating inter-limb asymmetry are not uniform, which makes it difficult to compare the inter-limb asymmetry across studies. Therefore, whether the asymmetry (16.72%) in single-leg CMJ height demonstrated in male fencers in the present study indicates increased risk of sport injury is not clear. Prospective-design study using functional jumping tests is required to investigate the effects of inter-limb asymmetry in lower-limb power on injury risk in child athletes (both boys and girls), since the present study has demonstrated inter-limb asymmetries in jump performance in 9-11 y old athletes.

The present findings showed a significant bilateral difference of CMJ height for boys while not for girls (Figure 5.1A), which indicated that sex might be an important factor when evaluating the bilateral difference in lower-limb power for child athletes. Practitioners should include both boys and girls when assessing the bilateral difference in lower-limb power for child athletes, and pay attention to the difference in asymmetry profile between sexes. Also, we suggest future research consider how to adjust for different sexes when investigating the association between inter-limb asymmetry in lower-limb power and the risk of sport injury. To date, there is a paucity of research examining the effect of sex on bilateral difference in lower-limb power in child athletes, which makes it difficult to compare our results with the work of others. Our result is contradictory to previous findings generated from high-school and adult-age athletes reporting that females are more likely to develop inter-limb asymmetry in leg strength/power in sport training (Brophy et al., 2009; Owens et al., 2011). Additional research with a sample in various age stages is required to examine whether age accounts for the differences found between our findings and previously reported literature.

5.4.2 Dynamic balance

Inter-limb asymmetry in performance of the SEBT (and Y Balance Test) has been reported in youth athletes aged between 12-17 y (Gorman et al., 2012; Lisman et al., 2019; Madruga-Parera et al., 2019; Miller et al., 2017; Pardos-Mainer et al., 2019; Steinberg et al., 2020). However, there is a lack of research focusing on children below 12 y. Our results demonstrated a main effect of limb for posterolateral reach distance without interaction between variables, indicating that fencers and taekwondo athletes in childhood (aged 9-11 y) also show bilateral differences in dynamic balance. Inter-limb asymmetry was shown in both the laterally and non-laterally dominant sport group, and no difference was found in the amount of inter-limb asymmetry between sport groups in each sex, suggesting the influence of leg preference (preferred vs. non-preferred leg) versus the influence of lateral dominance in sports (laterally vs. non-laterally dominant sport).

Studies have reported higher injury risk in high-school (Plisky et al., 2006) and collegiate (Smith et al., 2015) athletes when there is an inter-limb asymmetry in anterior reach distance greater than 4 cm. The inter-limb asymmetry in SEBT (or Y Balance Test) performance indicates a reduced dynamic postural control when establishing a unilateral stance using the weak-performance side, which may increase the injury risk (Mahajan, 2017). However, the reach distance reported by the previous research (Plisky et al., 2006; Smith et al., 2015) was not normalized to limb length. Gribble and Hertel (2003) suggested that when utilizing SEBT performance for clinical or experimental purposes, the reach distance should be normalized to limb length to ensure the accuracy of comparison of performance between participants. By normalizing the reach distance to limb length, we found the greatest magnitude of asymmetry was in posterolateral direction, with both boys and girls in the fencing group and boys in the taekwondo group showing inter-limb asymmetry above 10%. Future research is required to explore the association between inter-limb asymmetry in SEBT performance (normalized to limb length) and risk of sport injury in child athletes.

Our results showed a limb by sex interaction for posteromedial reach distance. Girls showed a significant bilateral difference of posteromedial reach distance while boys did not (Figure 1E), indicating that practitioners should pay attention to the difference between sexes when assessing the inter-limb asymmetry in dynamic balance for child athletes. Moreover, the difference between sexes should be addressed when examining the effects of inter-limb asymmetry in dynamic balance on injury risk, which has been overlooked in previous research. To date, there is a lack of research concerning the effects of sex on inter-limb asymmetry in dynamic balance in children from the literature. Our results are not consistent with previous findings generated from high-school athletes reporting female high-school athletes demonstrated less inter-limb asymmetry in anterior reach distance compared with their male counterparts (Gorman et al., 2012; Miller et al., 2017). It is unclear whether the disparity between our findings and previous literature is associated with the difference of age across samples. Thus, we suggest future research examine the effects of sex on inter-limb asymmetry in dynamic balance with athletes at various age stages.

In addition, by comparing the performance between sport groups, the taekwondo group demonstrated significantly greater posteromedial, posterolateral, and composite reach distance compared to the fencing group. The fact that taekwondo training places much emphasis on the development of flexibility (Thompson & Vinueza, 1991) may facilitate the SEBT performance in the taekwondo group as the flexibility is an important property contributing to SEBT performance (Gribble & Hertel, 2003). Nevertheless, this conclusion needs to be further examined by future research as flexibility was not measured in the present study. Low performance in the SEBT has been associated with increased injury risk. Butler et al. (2013) reported that male college football players with a composite reach distance below 89.60% limb length in the SEBT were 3.5 times more likely to have non-contact lower-limb injuries in the following season. High-school basketball players with a composite reach distance below 94% limb length in SEBT were 6.5 times more likely to have lower-limb injuries (Plisky et al., 2006); however, the difference between sexes has not been investigated. When evaluating the reach distance in the SEBT (and the Y Balance Test) and utilizing related findings, practitioners should be mindful of using the reported values due to the lack of a standardized protocol outlining the operation of the tests (Coughlan et al., 2012). Specifically, the position of the standing foot in the test was inconsistent in the literature, which affected the reach distance in each direction. In the present study, participants unilaterally stood at the convergence of the reach direction lines with placing the middle part of the foot on the convergence (Gribble & Hertel, 2003; Mahajan, 2017), instead of placing the most distal part of the foot behind the convergence, or placing the most proximal part of the foot before the convergence. This position is recommended because it is not biased towards the forward reaching (anterior) or backward reaching (posteromedial, posterolateral), and participants can finish the reaching for all the directions without moving the standing leg. Due to the differences mentioned above (age, sex, and testing protocol), it may not be rational to directly make comparisons between our results and the values reported by previous research (Butler et al., 2013; Plisky et al., 2006). Furthermore, prospective-designed research aimed at investigating the effects of SEBT (or Y Balance Test) performance on risk of sport injury in child athletes (for each sex) is needed.

5.4.3 Additional considerations

Although the length of training in the taekwondo group was greater compared to the fencing group, a bilateral difference was significant in jump and SEBT (posterolateral) performance in both sport groups and no difference was shown in the amount of inter-limb asymmetry between sport groups in each sex. Therefore, the difference in length of training between sport groups may not impact the findings regarding inter-limb asymmetry. However, the difference in length of training may impact the absolute performance in the SEBT as the taekwondo group showed greater reach distance compared to the fencing group in posteromedial, posterolateral, and composite reach distance. As the SEBT challenges a general ability including proprioception, flexibility, strength, and balance (Gribble & Hertel, 2003), we speculate that the greater length of training may benefit for the improvement of the general ability in the taekwondo group, and contribute to their better performance in the SEBT compared to the fencing group.

In addition, the girls were further away from their peak height velocity compared to the boys in the present study while no difference in age was found between sexes, which is abnormal as girls generally experience their growth spurt before boys (Haywood & Getchell, 2020). Where this abnormality comes from is uncertain. All participants in the present study were children with

East Asian ethnicity, whereas the equation (Mirwald et al., 2002) we used to calculate peak height velocity were generated from Canadian children. It is unclear whether the ethnicity background of the participants has influence on the calculation of the peak height velocity. It is also unclear whether this abnormality would impact results of inter-limb asymmetry in this study.

Previous studies (Knapik et al., 1991; Plisky et al., 2006; Schiltz et al., 2009; Smith et al., 2015) reporting a cut-off value as an indicator for increased injury risk have involved athletes from a wide range of sports (e.g., soccer, field hockey, tennis, and basketball), but there is a lack of research focusing on laterally dominant sports. Gray et al. (2016) has reported that the bilateral asymmetry seen in the abdominal muscles of cricket fast bowlers is likely adaptions required to perform this sport, and it may not always be detrimental to these athletes. More evidence is required to investigate whether or not the inter-limb asymmetry in laterally dominant sports is formed to meet the physical demands of these sports and as such be important for injury prevention.

5.4.4 Limitations

Sex and sport group were included as factors in this study, whereas age was not analyzed as a factor because of the limited number of participants. The discrepancy of findings between the present study and previous research regarding the effects of sex on bilateral difference may be related with age. Future research needs to explore the effects of age, and the interaction between age and sex on inter-limb asymmetry in lower-limb functional performance. Additionally, there are only nine girls in each sport group, and future research with larger sample size for each sex is warranted. A further limitation is the inability to include multiple sport disciplines into each pattern of sport (laterally and non-laterally dominant sport).

The present study mainly discussed inter-limb asymmetry in jump performance and dynamic balance, whereas the absolute performance of each side was not fully discussed. When using inter-limb asymmetry as a measurement for the purpose of injury prevention, it should be noted that high symmetry does not always indicate a positive outcome as poor performance on both limbs will still be categorized as symmetrical. We suggest including both the measurements of inter-limb asymmetry and the absolute performance of the two sides in practical evaluation.

5.5 Conclusion

Childhood-age athletes (9-11 y) in both laterally dominant and non-laterally dominant sports showed inter-limb asymmetry in jump performance and dynamic balance. Practitioners should be mindful of the effects of inter-limb asymmetry in lower-limb functional performance on risk of sport injury in this cohort of athletes. Sex should be an important consideration when evaluating bilateral difference in lower-limb power and dynamic balance in childhood-age athletes.

Chapter 6: Asymmetric Limb Performance Associated with Increased Injury Risk: A Prospective Study in Pediatric-Age Athletes

The purpose of this chapter was to examine whether inter-limb asymmetry in lower-limb functional performance can predict non-contact lower-limb injury in pediatric-age athletes. More than 400 taekwondo athletes (6-17 y) were assessed for inter-limb asymmetries in lower-limb functional performance as a baseline, and then prospectively traced for non-contact lower-limb injury for 12 months.

6.1 Introduction

The most common injuries in sport activities occur to the lower limbs (Hootman et al., 2007; Powell & Barber-Foss, 1999), with the ankle and knee being the most frequently injured locations (Emery & Tyreman, 2009; Emery et al., 2006). Although contact injuries account for the majority of sport injuries (Bastos et al., 2013; Hootman et al., 2007), some non-contact injuries (e.g., ligament sprains and muscle strains) were the most common sport injuries (Emery et al., 2006; Hootman et al., 2007). In the sport of taekwondo, non-contact injuries including sprains and strains to the lower extremities were also the most common injuries (Jeong, Ha, Jeong, O'Sullivan, & Lee, 2021; Thomas, Thomas, & Vaska, 2017). Moreover, non-contact injuries are often caused by intrinsic factors (e.g., neuromuscular disorders, being unfit, training overloaded), which may be the most modifiable risk factors (Gonell et al., 2015; Read et al., 2018). A better understanding of the modifiable risk factors for non-contact lower-limb injury is needed, so that efficient intervention programming and prevention strategies can be developed.

The inter-limb asymmetry in functional performance has been suggested as a modifiable risk factor for sport injury (Knapik et al., 1991; Smith et al., 2015). Focusing on the lower extremities, inter-limb asymmetry may potentially place both legs at a heightened risk of injury in sport; the strong leg may sustain excessive stress because of increased dependence and continuous high loading on that side, whereas the weak leg may be compromised to sustain even average stress (Ford et al., 2003). To date, the effects of inter-limb asymmetry in lower-limb strength/power and dynamic balance (or postural control) on risk of non-contact lower-limb injury have been widely examined (Brumitt et al., 2013; De Blaiser et al., 2021; Fousekis et al., 2011; Fousekis et al., 2012; Smith et al., 2015; Warren et al., 2020). Inter-limb asymmetries in single-leg hop, triple hop, and crossover hop distance significantly predict risk of non-contact lower-limb injury in female athletes of a collegiate athletic program (Warren et al., 2020). In regard to the dynamic balance (measured with the SEBT and the Y Balance Test), a 4 cm or greater inter-limb asymmetry in posterolateral reach distance in Y Balance Test indicates greater risk of patellofemoral pain in male military recruits (Nakagawa et al., 2020). However, there are also a number of studies showing no association between inter-limb asymmetries (in lower-limb strength/power and dynamic balance) and sport injury (Brumitt et al., 2019; Butler et al., 2013; Lai et al., 2017; Markovic et al., 2020). It is difficult to make a clear statement regarding the validity of using inter-limb asymmetry in lower-limb functional performance to predict sport injury, due to the highly inconsistent findings.

An important limitation in the current literature is the paucity of research focusing on pediatric-age athletes. Compared with adults, pediatric-age athletes are more vulnerable to sport injuries because of the incomplete growth and maturation of the cartilage and musculoskeletal system

(Cuff et al., 2010; Radelet et al., 2002). According to available data, inter-limb asymmetries in jump performance (assessed with single-leg CMJ) (Read et al., 2018) and dynamic balance (assessed with the Y Balance Test) (Read et al., 2020) significantly predict non-contact lower-limb injury in pediatric-age male athletes. However, no evidence is available for pediatric-age female athletes. Moreover, few studies have addressed the potential effects of sex on the relationship between inter-limb asymmetry and lower-limb injury. Therefore, the main purpose of the present investigation was to determine whether inter-limb asymmetries in functional performance (jump performance and dynamic balance) can predict non-contact lower-limb injury in pediatric-age male and female taekwondo athletes. It was hypothesized that greater inter-limb asymmetries in jump performance and dynamic balance indicated higher risk of non-contact lower-limb injury in both sexes.

6.2 Methods

6.2.1 Design

This study employed a prospective design to examine the effects of inter-limb asymmetry in functional performance on risk of non-contact lower-limb injury in pediatric-age male and female taekwondo athletes. Inter-limb asymmetries in jump performance and dynamic balance were assessed for each participant at baseline. The basic information (height, body mass, leg preference) of the participants were also examined in the baseline tests. Participants were then traced prospectively for non-contact lower-limb injury for 12 months following the baseline tests.

6.2.2 Participants

Participants were recruited from June 2019 to November 2019. Based on different parameters reported by previous studies (Brumitt et al., 2013; Plisky et al., 2006), the sample size was determined to be around 90 or 300 (within each sex). A total of 456 pediatric-age taekwondo athletes (348 boys, 108 girls) between 6 and 17 y from eight taekwondo clubs volunteered to participate in the present study. All participants had at least 12 months of training experience (specialized at taekwondo) and maintained regular training (≥ 1.5 hours/day, ≥ 3 days/week) in the preceding 12 months before participation. Participants were excluded if an injury limited their performance on baseline tests. The investigation received approval from, and was executed in exact accordance with, the ethical guidelines set forth by the University of British Columbia's Clinical Research Ethics Board and the Shandong Sport University's Human Ethics Committee for research involving human participants according to the standards established by Declaration of Helsinki. Written informed consent was received from parents/guardians of participants, and written informed assent was obtained from participants.

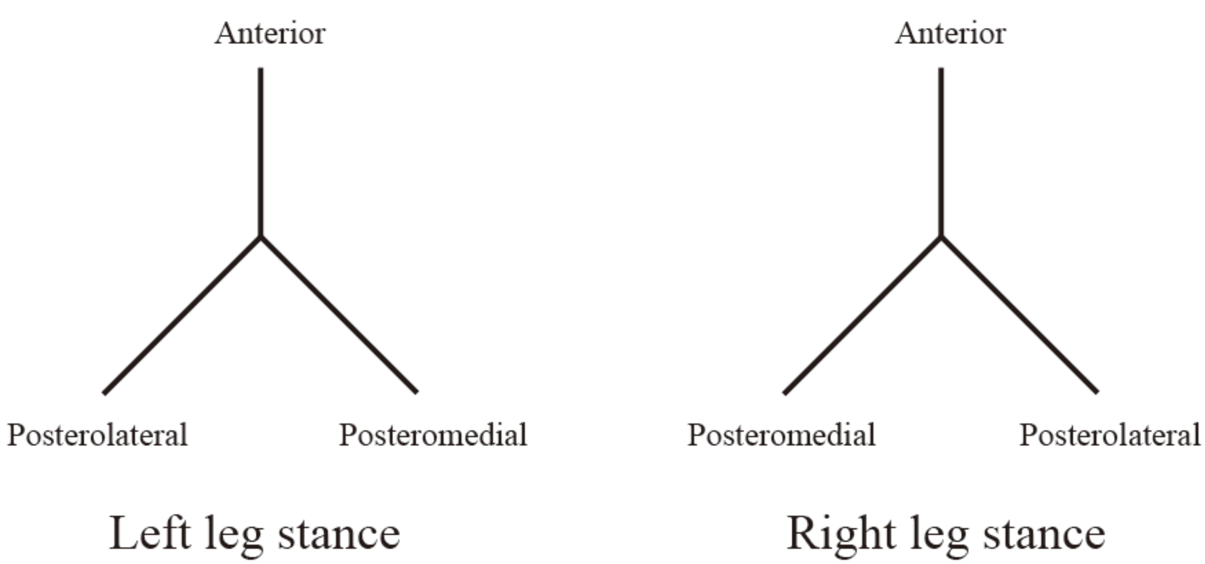
6.2.3 Assessment of baseline asymmetry

Inter-limb asymmetry in leg power was assessed using unilateral jump tests (single-leg CMJ, hop, and triple-hop). Specific protocols for measurements have been reported in Chapter 5. The goal of the single-leg CMJ test was to obtain the maximum jump height of each leg. Participants stood in an upright position with feet positioned shoulder width apart. Hands were placed on hips during the entire movement to reduce the impact of arm movement (Impellizzeri et al., 2007). To start the test, the participant lifted one leg to a comfortable position, and then performed a countermovement to a comfortable depth followed by a vertical jump with full strength. The entire movement was recorded with an iPhone 6s (Apple, Inc., USA) at 240 Hz. The jump height (cm) was calculated based on the flight time of the jump by identifying the take-off and landing frames using the “My Jump” iPhone application, which has been reported a valid and reliable method (Haynes et al., 2019).

The goal of the single-leg hop and triple-hop test was to obtain the maximum horizontal distance of one hop and three consecutive hops, respectively. Participants started with a unilateral standing position and toes of the supporting leg behind the starting line. For the one hop test, participants performed a forward hop as far as possible and land firmly using the same leg. Failure to perform a firm landing was viewed as an invalid trial. The hop distance (cm) from the starting line to the participant’s landing heel was measured and recorded. For the triple-hop test, participants performed three consecutive forward hops as far as possible using the same leg, with the intention of reducing the floor contact time of the first two landings as much as possible. The landing of the last hop had to be firm. Failure to perform a firm landing at the last hop was viewed as an invalid trial. The horizontal hop distance (cm) from the starting line to the participant’s final landing heel was measured and recorded. Three valid trials were required for each leg in each jump test. The average jump height/distance of the three trials of each leg in each test was used for analysis.

Inter-limb asymmetry in dynamic balance was assessed using the SEBT which is a valid and and reliable (ICC = 0.78-0.96) (Hertel et al., 2000) test developed by Gray (1995). The goal of the SEBT was to obtain the maximum reach distance along three directions (anterior, posteromedial, and posterolateral) using the contralateral limb while maintaining a unilateral stance with solid foundation (Coughlan et al., 2012). The sketch of the SEBT is presented in Figure 6.1. While unilaterally standing at the convergence of reach direction lines, participants were asked to reach as far as possible with the other leg along each of the three directions (in the order of anterior, posteromedial, and posterolateral direction), lightly touching each line using the most distal part of the reaching foot without disrupting the established balance during the entire movement. The point where the most distal part of the foot reached was marked with erasable ink on each direction line. Each participant performed three trials (each trial with three directions) using each leg. Participants took this test barefoot to eliminate the effects of shoes on balance and stability. The trial was viewed as invalid when participants failed to maintain the unilateral stance, moved or lifted the standing foot from the convergence of lines, or failed to return the reaching foot to the original position (Plisky et al., 2006). The greatest reach distance (cm) from the convergence of lines to the point where the most distal part of the foot reached in the three trials for each direction of each leg was used for analysis.

Figure 6.1 The sketch of the Star Excursion Balance Test



6.2.4 Procedure of the baseline tests

Each Participant finished all assessments in a dedicated testing area at the club in one visit. First, participants took anthropometric measurements including body height (cm), leg length (cm), and body weight (kg). Limb dominance was examined by letting the participant kick a soccer ball, and the limb which the participant preferred for the ball kicking was defined as the dominant leg. Participants then completed all assessments of leg power and dynamic balance in one session. At the start of the session, each participant completed stretching and a five-minute jog to warm-up. Participants were then provided with test instructions and received time to practice until they were familiar with each test. For the SEBT, participants performed at least six practice trials in each direction to account for learning effects (Hertel et al., 2000). Following test familiarization, participants had a rest for five minutes. Participants then completed the tests in the following order: single-leg CMJ, hop, triple hop, and SEBT, with a one-min rest between each test. The starting leg was randomly selected to reduce the order effect. The same tester scored all the tests for all participants.

6.2.5 Injury surveillance

Participants were prospectively traced for non-contact lower-limb injury for 12 months following the baseline tests. The coaches and/or athletic trainers of each club recorded each injury on standardized forms. An injury was defined as a medical problem (both acute and chronic) to lower extremities occurred during taekwondo training or competition via a non-contact mechanism that required the athlete to be removed from that day's event or prevented the athlete from participating in the subsequent training or competition (Brumitt, Mattocks, et al., 2020;

Butler et al., 2013). Lower-limb injuries that occurred at a time other than during taekwondo training or competition, or caused by contact with equipment or another player, were excluded. Only injuries that met the injury definition were included for analysis. If a participant sustained more than one injury during the follow-up period, only the first injury was included (Read et al., 2018). To protect privacy, all participants were provided an individualized identification code for the injury-recording forms. The primary contact of the study collected the injury-recording forms from the coaches and/or athletic trainers every three months, and confirmed the details of injury information with the coaches and/or athletic trainers to reduce report bias.

6.2.6 Data analyses

Participants lost to follow up were excluded from data analyses. Reach distances measured in the SEBT were normalized to leg length (leg length%). The composite reach distance of the three directions for each leg was calculated by averaging the reach distances of the three directions. The amount of inter-limb asymmetries in jump performance and the SEBT reach distance (normalized to leg length) at each direction were quantified using an equation modified from previous studies (Sugiyama et al., 2014; Wong et al., 2007): Asymmetry = (Stronger Limb − Weaker limb) × 2 / (Stronger Limb + Weaker limb) × 100 (%). The asymmetries in SEBT reach distance were also quantified using the absolute difference (cm) between limbs.

6.2.7 Statistical analyses

The reliability of each jump test was examined using intraclass correlation coefficient (ICC). Normality and homoscedasticity assumption of the continuous data were examined using the Kolmogorov-Smirnov and Levene’s test, respectively. Participants with missing data for baseline tests were excluded from related analyses. Mann Whitney U test was employed to compare age, length of training, height, and body mass between boys and girls as data were not normally distributed. Chi-square test was employed to compare the proportion of injured athletes between boys and girls. Mann Whitney U test was employed to compare the magnitude of inter-limb asymmetry for each parameter between the injured and non-injured athletes within each sex as data distribution was not normal; effect size was reported using the correlation coefficient ($r = Z/\sqrt{n}$).

Receiver operating characteristic (ROC) curves were used to determine the optimal cut-off points for predicting injury in each sex on the basis of each predictor variable (inter-limb asymmetry in single-leg CMJ height, hop distance, triple-hop distance, and SEBT reach distance [anterior, posteromedial, posterolateral, and the composite of the three directions]). The optimal cut-off point on each ROC curve was identified as the asymmetry that maximized both sensitivity and specificity. For each predictor variable with an optimal cut-off point in ROC curve, a subsequent logistic regression controlling for age [to adjust the effect of age on asymmetries (Sannicandro, Quarto, et al., 2014) and injury (Cuff et al., 2010)] was used to calculate the adjusted odds ratio (OR) and 95% confidence interval (CI) for injury, comparing the high-risk group (as determined by the cut-off point in ROC curve) with the referent group.

Further analysis was completed with each inter-limb asymmetry as a continuous variable. Each predictor variable (inter-limb asymmetry in single-leg CMJ height, hop distance, triple-hop distance, and SEBT reach distance [anterior, posteromedial, posterolateral, and the composite of the three directions]) was entered into a separate multivariate logistic regression controlling for age to calculate the adjusted OR and 95% CI for injury. All statistical analyses were conducted using SPSS 23 with alpha level set *a priori* at 0.05.

6.3 Results

Participant characteristics are presented in Table 6.1. A complete 12-month follow-up was obtained in 415 athletes (91%; 318 boys, 97 girls), among whom 98 athletes (70 boys [22.0%], 28 girls [28.9%]) sustained non-contact lower-limb injuries leading to time loss (≥1-d). No significant difference in injury rate was shown between boys and girls ($p = 0.164$). Ankle and knee were the most frequently injured locations in both sexes (Table 6.2).

Table 6.1 Characteristics of the participants

Variables	**Boys (318)**	**Girls (97)**	***P***
Age (y)	9.03 ± 2.02	9.32 ± 2.37	0.446
Length of training (y)	2.52 ± 1.36	2.36 ± 1.09	0.541
Height (m)	1.40 ± 0.12	1.41 ± 0.12	0.554
Body mass (kg)	36.45 ± 12.28	36.70 ± 12.21	0.765
Injury			
Injured (n, %)	70 (22.0%)	28 (28.9%)	0.164
Non-injured (n, %)	248 (78.0%)	69 (71.1%)	

Table 6.2 Frequency of injury locations

Variables	**Boys**		**Girls**	
	n	Percentage	n	Percentage
Hip	2	2.9%	0	0%
Thigh	7	10.0%	6	21.4%
Knee	23	32.9%	7	25.0%
Calf	5	7.1%	0	0.0%
Ankle	24	34.3%	14	50.0%
Foot	9	12.9%	1	3.6%
Total	70	100%	28	100%

Descriptive statistics for each measurement in jump tests and SEBT were shown in Table 6.3. The results of ICC calculation showed an excellent reliability of each measurement in the single-leg jump tests for each leg in both boys and girls (Table 6.3).

Table 6.3 Descriptive statistics for each measurement and the intra-class correlation coefficient

Tests and variables	Boys			Girls		
	Performance	ICC	95% CI	Performance	ICC	95% CI
Jump tests						
CMJ (cm)						
DL	11.18 ± 3.91	0.958	0.863-0.903	11.24 ± 2.90	0.920	0.888-0.944
NDL	10.94 ± 3.90	0.944	0.933-0.954	10.96 ± 2.85	0.919	0.886-0.943
Hop (cm)						
DL	109.61 ± 24.78	0.966	0.958-0.972	106.89 ± 19.83	0.940	0.918-0.958
NDL	107.37 ± 24.76	0.959	0.951-0.967	104.84 ± 20.75	0.936	0.912-0.955
Triple-hop (cm)						
DL	347.65 ± 81.67	0.981	0.977-0.985	340.70 ± 61.31	0.974	0.962-0.982
NDL	341.50 ± 83.36	0.982	0.978-0.986	332.47 ± 59.86	0.983	0.976-0.989
SEBT						
Anterior RD (cm)						
DL	68.65 ± 8.66	—	—	67.94 ± 8.05	—	—
NDL	69.02 ± 8.94	—	—	68.88 ± 8.01	—	—
Posteromedial RD (cm)						
DL	57.04 ± 11.05	—	—	56.86 ± 10.13	—	—
NDL	57.55 ± 10.79	—	—	58.39 ± 11.10	—	—
Posterolateral RD (cm)						
DL	52.10 ± 12.29	—	—	52.58 ± 11.57	—	—
NDL	50.21 ± 11.74	—	—	52.17 ± 12.10	—	—
Composite RD (cm)						
DL	59.26 ± 9.90	—	—	59.13 ± 9.17	—	—
NDL	58.93 ± 9.79	—	—	59.82 ± 9.56	—	—
Anterior NRD (%)						
DL	103.92 ± 9.36	—	—	102.64 ± 8.73	—	—
NDL	104.53 ± 9.71	—	—	104.12 ± 9.56	—	—
Posteromedial NRD (%)						
DL	85.98 ± 12.40	—	—	85.63 ± 12.60	—	—
NDL	86.77 ± 11.79	—	—	88.06 ± 12.60	—	—
Posterolateral NRD (%)						
DL	78.60 ± 15.17	—	—	79.26 ± 13.86	—	—
NDL	75.66 ± 14.05	—	—	78.33 ± 15.62	—	—
Composite NRD (%)						
DL	89.50 ± 10.63	—	—	89.18 ± 10.21	—	—
NDL	88.98 ± 10.24	—	—	90.17 ± 10.87	—	—

ICC, intra-class correlation coefficient; CI, confidence interval; CMJ, countermovement jump; DL, dominant leg; NDL, non-dominant leg; SEBT, Star Excursion Balance Test; RD, reach distance; NRD, normalized reach distance.

The magnitude of inter-limb asymmetry in each measurement of jump tests and SEBT was compared between the injured and non-injured athletes within each sex (Table 6.4). The injured athletes showed significantly greater magnitude of inter-limb asymmetry in single-leg CMJ height (Z = -4.376, p = 0.000, effect size = 0.246) and triple-hop distance (Z = -2.293, p = 0.022, effect size = 0.132) compared to the non-injured athletes in boys.

Table 6.4 The magnitude of inter-limb asymmetry in each measurement in injured vs. non-injured athletes (Mann Whiney U tests)

Asymmetry (%)	Boys		Girls	
	Injured	Non-Injured	Injured	Non-Injured
Jump tests				
CMJ	18.86 ± 13.75	11.00 ± 9.24[a]	16.40 ± 14.27	9.65 ± 7.18
Hop	7.39 ± 6.24	6.02 ± 5.60	7.92 ± 9.46	5.50 ± 4.28
Triple-hop	8.14 ± 8.10	5.61 ± 5.99[b]	6.33 ± 5.34	4.49 ± 4.01
SEBT				
Anterior RD	3.35 ± 2.63	3.60 ± 3.22	3.22 ± 4.26	4.23 ± 2.80
Posteromedial RD	5.72 ± 4.43	5.03 ± 3.66	3.70 ± 3.56	4.89 ± 4.20
Posterolateral RD	5.95 ± 4.53	5.94 ± 5.13	4.61 ± 4.15	6.60 ± 5.35
Composite RD	3.56 ± 2.78	3.19 ± 2.59	2.28 ± 1.70	3.06 ± 2.36
Anterior NRD	4.91 ± 3.93	5.24 ± 4.47	4.73 ± 5.79	6.29 ± 4.36
Posteromedial NRD	10.06 ± 7.82	9.01 ± 6.62	6.33 ± 5.58	8.70 ± 7.64
Posterolateral NRD	11.76 ± 9.43	12.64 ± 13.73	9.55 ± 8.55	13.08 ± 11.30
Composite NRD	5.97 ± 4.65	5.49 ± 4.70	3.90 ± 2.73	5.26 ± 4.30

CMJ, countermovement jump; SEBT, Star Excursion Balance Test; RD, reach distance; NRD, normalized reach distance.
[a] $p < 0.05$
[b] $p < 0.01$

Results of the ROC curve analyses are presented in Table 6.5. The ROC curve for asymmetry in single-leg CMJ height determined 15.28% as the cut-off point for predicting non-contact lower-limb injury in boys (area under curve = 0.66; 95% CI: 0.58-0.75, p = 0.000) with a sensitivity of 60.3% and specificity of 77.5%. ROC curves for the other asymmetries failed to identify a cut-off point that would maximize sensitivity and specificity. The subsequent logistic regression

(Table 6.6) showed that ≥15.28% asymmetry in single-leg CMJ height was significantly associated with greater risk of non-contact lower-limb injury in boys after adjusting for age (adjusted OR [≥15.28% vs. <15.28%], 5.98; 95% CI, 3.35-10.69; p = 0.000).

Table 6.5 Receiver Operating Characteristics curves for predicting injury based on asymmetries in pediatric-age taekwondo athletes

Asymmetry	Boys				Girls			
	n	Area under curve (95% CI)	*P*	Cut-off point	n	Area under curve (95% CI)	*P*	Cut-off point
Jump tests								
Single-leg CMJ	317	0.66 (0.58-0.75)	0.000	15.28%	97	0.63 (0.47-0.78)	0.052	—
Single-leg hop	313	0.60 (0.49-0.65)	0.086	—	96	0.54 (0.41-0.68)	0.515	—
Single-leg triple hop	300	0.64 (0.51-0.67)	0.021	—	93	0.61 (0.48-0.73)	0.104	—
SEBT								
Anterior RD	288	0.48 (0.40-0.57)	0.691	—	94	0.33 (0.21-0.46)	0.012	—
Posteromedial RD	288	0.53 (0.45-0.62)	0.424	—	94	0.41 (0.29-0.54)	0.183	—
Posterolateral RD	288	0.51 (0.43-0.58)	0.886	—	94	0.39 (0.26-0.51)	0.083	—
Composite RD	288	0.53 (0.45-0.62)	0.417	—	94	0.42 (0.29-0.54)	0.201	—
Anterior NRD	288	0.48 (0.39-0.56)	0.555	—	94	0.34 (0.22-0.47)	0.018	—
Posteromedial NRD	288	0.53 (0.44-0.62)	0.461	—	94	0.43 (0.31-0.55)	0.283	—
Posterolateral NRD	288	0.50 (0.44-0.57)	0.953	—	94	0.41 (0.28-0.53)	0.151	—
Composite NRD	288	0.53 (0.45-0.61)	0.489	—	94	0.43 (0.30-0.56)	0.277	—

CMJ, countermovement jump; SEBT, Star Excursion Balance Test; RD, reach distance; NRD, normalized reach distance; CI, confidence interval.

Table 6.6 Odds ratio with single-leg countermovement jump height asymmetry in pediatric-age male taekwondo athletes

Asymmetry	n	Injured	Adjusted OR	95% CI	*P*
<15.28%	219	27 (12.3%)	1.00	referent	0.000
≥15.28%	98	43 (43.9%)	5.98	3.35-10.69	

OR, odds ratio; CI, confidence interval.

When entering each asymmetry (as a continuous variable) into a separate logistic regression controlling for age (Table 6.7), inter-limb asymmetries in single-leg CMJ height (adjusted OR, 1.07 for increase of 1 cm; 95% CI, 1.04-1.09; $p < 0.001$), hop distance (adjusted OR, 1.04 for increase of 1 cm; 95% CI, 1.00-1.09; $p < 0.05$), and triple-hop distance (adjusted OR, 1.06 for increase of 1 cm; 95% CI, 1.02-1.10; $p < 0.01$) were significantly associated with non-contact lower-limb injury in boys. In girls, only the inter-limb asymmetry in single-leg CMJ height (adjusted OR, 1.07 for increase of 1 cm; 95% CI, 1.02-1.12; $p < 0.01$) was significantly associated with non-contact lower-limb injury. No significant association ($p > 0.05$) was found between inter-limb asymmetry in SEBT performance and non-contact lower-limb injury.

Table 6.7 Odds ratios with asymmetries entered as continuous variables to predict injury in pediatric taekwondo athletes

Asymmetry	Boys		Girls	
	n	Adjusted OR (95% CI)	n	Adjusted OR (95% CI)
Jump tests				
SLCMJ	317	1.07 (1.04-1.09)[a]	97	1.07 (1.02-1.12)[b]
SL hop	313	1.04 (1.01-1.09)[c]	96	1.06 (0.98-1.14)
SL triple hop	300	1.06 (1.02-1.10)[b]	93	1.09 (0.99-1.20)
SEBT				
Anterior RD	288	0.97 (0.88-1.07)	94	0.89 (0.76-1.05)
Posteromedial RD	288	1.04 (0.97-1.12)	94	0.92 (0.81-1.05)
Posterolateral RD	288	1.00 (0.95-1.06)	94	0.91 (0.82-1.02)
Composite RD	288	1.04 (0.94-1.16)	94	0.84 (0.66-1.06)
Anterior NRD	288	0.98 (0.92-1.05)	94	0.92 (0.82-1.03)
Posteromedial NRD	288	1.03 (0.99-1.07)	94	0.95 (0.88-1.02)
Posterolateral NRD	288	1.00 (0.97-1.02)	94	0.96 (0.92-1.01)
Composite NRD	288	1.02 (0.97-1.08)	94	0.90 (0.79-1.03)

SL, single-leg; CMJ, countermovement jump; SEBT, Star Excursion Balance Test; RD, reach distance; NRD, normalized reach distance; OR, odds ratio; CI, confidence interval.
[a] $p < 0.001$
[b] $p < 0.01$
[c] $p < 0.05$

6.4 Discussion

The inter-limb asymmetry in lower-limb power was assessed using unilateral jump tests in the present study. A number of studies have assessed inter-limb asymmetry in leg strength using isokinetic and isometric strength tests and associated it with lower-limb injury (De Blaiser et al., 2021; Fousekis et al., 2011; Fousekis et al., 2012). However, the isometric and isokinetic strength tests may not be optimal tests for sports characterized by quick muscle actions involving stretch-shortening cycle (Impellizzeri et al., 2007). Instead, jump tests are recommended for the assessment of lower-limb strength/power because of the required stretch-shortening cycle and high-rate force production (Impellizzeri et al., 2007). Unilateral jump tests are recommended because the movements of unilateral jumps rely on the force generated from one side, and the performance of the dominant and non-dominant side separately were more indicative for the difference between the two sides (Benjanuvatra et al., 2013). Further, unilateral landing depicts one of the most common mechanism of non-contact injuries such as the ACL tear (Barber-Westin & Noyes, 2017; Heil et al., 2020). To date, unilateral jump tests have been used for the assessment of inter-limb asymmetry in lower-limb power in a wide range of sports including volleyball (Brumitt et al., 2013), soccer (Markovic et al., 2020; Read et al., 2018; Sieland et al., 2020), ski race (Steidl-Muller et al., 2018), and basketball (Brumitt et al., 2013). In the sport of taekwondo, all the kicks are performed unilaterally and characterized by quick muscle actions involving stretch-shortening cycle (Turner, 2009), which supports the utilization of the single-leg jump tests in assessing inter-limb asymmetry in lower-limb power in taekwondo athletes. In addition, the SEBT was employed to assess inter-limb asymmetry in dynamic balance in the present study, because this test examines the performance of dynamic postural control around a base of single-leg support (Gribble et al., 2012), mimicking the demand of taekwondo kicks in which pivoting on one leg to rotate the body with great dynamic postural control on the pivoting (supporting) leg is essential (Jlid, Maffulli, Souissi, Chelly, & Paillard, 2016).

6.4.1 Inter-limb asymmetry in jump performance and non-contact lower-limb injury

This is the first prospective study identifying a cut-off value for injury prediction in pediatric-age athletes on the basis of inter-limb asymmetry in jump performance. This is also the first prospective study to address the role of sex when examining the relationship between inter-limb asymmetry and sport injury in a cohort of pediatric-age athletes. The ROC curve for inter-limb asymmetry in single-leg CMJ height identified 15.28% asymmetry as the cut-off value for predicting non-contact lower-limb injury in males, although the sensitivity is not high (60.3%); however, no cut-off value for predicting injury was identified in females. The subsequent logistic regression demonstrated that males with ≥15.28% inter-limb asymmetry in single-leg CMJ height were 5.98 times (adjusted for age) more likely to sustain a non-contact lower-limb injury when compared with the referent group (<15.28% asymmetry), which corroborates the results of the ROC curve analysis. These findings suggest that 15.28% inter-limb asymmetry can be utilized as a cut-off value when using single-leg CMJ height to predict lower-limb injury in pediatric-age male athletes. With the utilization of this cut-off value, at risk male athletes can be monitored more closely, with the potential for preventive intervention.

Similar to the findings in the present study, two prospective studies have reported that 15% inter-limb asymmetry in isometric knee (Fousekis et al., 2011) and ankle (Fousekis et al., 2012) strength significantly predict lower-limb injury in professional male soccer players. However, the cut-off values should be used with caution in injury prediction. The equations used for calculating inter-limb asymmetry vary across studies, and different equations may lead to different solutions. Thus, this cut-off value (15%) may not represent the same amount of inter-limb asymmetry across studies. Moreover, the difference between testing protocols (e.g., isometric strength tests vs. unilateral jump tests) and sample characteristics (caused by age, sex) may also contribute to the discrepancy in findings. Therefore, the cut-off value (15.28%) reported in the present study is only applicable to pediatric-age male athletes when using inter-limb asymmetry (quantified using our equation) in single-leg CMJ height to predict non-contact lower-limb injury.

Most studies have determined the relationship between inter-limb asymmetry in jump performance and sport injury by comparing the high vs. low-risk group based on a cut-off value (e.g., 15% inter-limb asymmetry). There is a lack of research using inter-limb asymmetry as a continuous variable to evaluate the risk of sport injury. Only one study has reported that the inter-limb asymmetry ([low-high]/high × 100 [%]) in peak landing vertical ground reaction force in single-leg CMJ was associated with non-contact lower-limb injury in U11-12 (OR = 0.90) and U15-16 (OR = 0.91) elite male soccer athletes (Read et al., 2018). Results in the present study demonstrate that the adjusted OR (to age) for an increase of 1% asymmetry in single-leg CMJ height is 1.07 in both sexes, which means that an increase of 10% asymmetry in single-leg CMJ height will increase the risk of non-contact lower-limb injury by 1.97 times in both sexes. In addition, the injured athletes demonstrated significantly greater amount of inter-limb asymmetry in single-leg CMJ height compared to the non-injured athletes in boys; a much higher amount of inter-limb asymmetry in single-leg CMJ height was also demonstrated in injured (16.40 ± 14.27) vs. non-injured (9.65 ± 7.18) athletes in girls, although no significance ($p > 0.05$) was shown. Cumulatively, these findings suggest that inter-limb asymmetry in single-leg CMJ performance can be a valid tool to evaluate risk of non-contact lower-limb injury in both sexes in pediatric-age athletes.

Regarding the relationship between inter-limb asymmetry in unilateral hop distance and injury, our results showed a difference between sexes. An increase of 10% inter-limb asymmetry in single-leg hop (adjusted OR = 1.04) and triple-hop (adjusted OR = 1.06) distance will increase the injury risk for males by 1.48 and 1.79 times, respectively, after adjusting for age. In addition, the injured athletes showed significantly greater amount of inter-limb asymmetry in single-leg triple-hop distance compared to the non-injured athletes in males. However, these asymmetries are not associated with injury in females, which suggests that they may not be appropriate for predicting non-contact lower-limb injury in pediatric-age female athletes. These findings indicate that sex difference should be an important consideration when using inter-limb asymmetry in unilateral hop performance to predict injury, which has been neglected in previous studies. Based on the present findings, it is recommended that practitioners examine males and females separately when using inter-limb asymmetry in unilateral hop and triple-hop distance to predict lower-limb injury. However, the exact mechanism of this difference (between sexes) was not clear. Future research with a large sample size is required to further examine the validity of using inter-limb asymmetry in unilateral hop distance to predict sport injury in pediatric-age female athletes.

6.4.2 Inter-limb asymmetry in dynamic balance and non-contact lower-limb injury

The present study demonstrated no association between inter-limb asymmetry in SEBT reach distance (absolute and normalized values) and non-contact lower-limb injury in either sex, suggesting that inter-limb asymmetry in dynamic balance assessed with the SEBT might not be appropriate for predicting non-contact lower-limb injury in pediatric-age athletes. Few comparable findings are available due to the lack of prospective research on pediatric-age athletes from the literature. Only one study has focused on pediatric-age athletes, and reported that inter-limb asymmetry (absolute difference) in anterior reach distance in the Y Balance Test associated with non-contact lower-limb injury in pre-peak height velocity (11.9 ± 1.1 y) and circa-peak height velocity (14.4 ± 0.9 y) male soccer athletes (Read et al., 2020). One potential reason for the inconsistency between findings may be the difference between sports (taekwondo vs. soccer), while the specific mechanism is not clear. Additionally, the present study involved pediatric-age athletes with a wide range of age (6-17 y), which may also affect the findings. Future research should consider examining the relationship between inter-limb asymmetry in dynamic balance and sport injury with pediatric-age athletes from other sports at each age stage.

Findings generated from adult athletes are also inconsistent. Most studies reported no association between inter-limb asymmetry in dynamic balance and sport injury (Brumitt et al., 2019; Brumitt, Sikkema, et al., 2020; Butler et al., 2013; De Blaiser et al., 2021; Hartley et al., 2018; Lai et al., 2017; Luedke et al., 2020; Manoel et al., 2020). In contrast, Smith et al. (2015) reported that ≥4 cm inter-limb asymmetry in anterior reach distance in Y Balance Test indicated greater risk of non-contact injury in collegiate athletes. In addition, Nakagawa et al. (2020) reported that ≥4.08 cm inter-limb asymmetry in posterolateral reach distance in Y Balance Test indicated greater risk of patellofemoral pain in male military recruits. The inconsistency between findings may be related to the difference in injury definition (e.g., contact vs. non-contact injury, requirement of time loss, lower-limb vs. entire-body injury) and participant characteristics (age, sex, sports).

Most studies quantified the inter-limb asymmetry of performance in the SEBT and Y Balance Test using the absolute reach distance, which may also contribute to the inconsistency of findings. Gribble and Hertel (2003) suggested that the reach distance measured in the SEBT and Y Balance Test should be normalized to leg length to ensure accuracy of comparison between participants or studies. We recommend future research include both the absolute side-to-side difference and normalized asymmetry (to leg length) when examining the effects of inter-limb asymmetry in dynamic balance on sport injury. In addition, we do not recommend using inter-limb asymmetry in reach distance in the SEBT (or the Y Balance Test) as the only tool to predict injury in clinical application, because most studies to date did not demonstrate a strong association with predicting sport injury.

6.4.3 Limitations

We acknowledge the limitations in the present study. It has been suggested that the effects of previous injury (Emery & Tyreman, 2009) and exposure time (Taunton et al., 2003) should be considered when evaluating injury risk; however, these two variables were not included as covariates in the present study. In addition, our sample consisted of a range of ages with pediatric-age athletes at varying stages of physical development, which might impact the results. The limited sample size of the female participants in the present study might also impact the results. Participants were not stratified based on age because of the need of a large sample size for the logistic regression analyses. Future research should consider to further explore the association between inter-limb asymmetry in lower-limb functional performance and sport injury by stratifying youth athletes into different age stages. Moreover, the magnitude of inter-limb asymmetry may change throughout the 12 months after the baseline test, while there was no follow-up test for further assessment in the present study. Considering the statistical analyses, the same data set for determining the cut-off point in ROC curve was used to examine the strength of the cut-off point for injury prediction (<15.28% vs. ≥15.28 asymmetry, Table 6.6), which might result in an inflated value of the OR. Findings also need to be extended from taekwondo to other sports.

The present study mainly focused on the inter-limb asymmetry, while the absolute performance of each side was not discussed. In practical application, we suggest including both the inter-limb asymmetry and the absolute performance of each side to predict/evaluate the risk of sport injury. In addition, the specific characteristics of the sport taekwondo was not fully discussed in the present study (all participants specialized in taekwondo), because we aimed to explore the validity of using inter-limb asymmetry in lower-limb functional performance to predict sport injury in youth athletes, instead of focusing on a certain sport. However, we acknowledge that the present findings need to be extended from taekwondo to other sports.

6.5 Conclusion

Inter-limb asymmetries in unilateral jump performance (single-leg CMJ height, hop distance, and triple-hop distance) can be utilized to predict lower-limb injury in pediatric-age athletes, while practitioners should pay attention to the difference between sexes. Inter-limb asymmetries in SEBT performance may not be appropriate for predicting non-contact lower-limb injury in pediatric-age athletes. These findings could stimulate further research and impact on the application of screening test for pediatric-age athletes aimed at reducing injury risk. Moreover, these findings provide a foundation for further investigations evaluating whether correction of the inter-limb asymmetry can prevent injury.

Chapter 7: The Effects of Fatigue on Asymmetry Between Lower Limbs in Functional Performance in Elite Child Taekwondo Athletes

The purpose of this chapter was to examine the effects of exercise-induced fatigue on inter-limb asymmetry in lower-limb functional performance in child athletes. Inter-limb asymmetries in lower-limb functional performance in 9-11 y old taekwondo athletes at the rested and fatigued state were examined and compared.

7.1 Introduction

Inter-limb asymmetry (or bilateral difference, bilateral asymmetry) is defined as the difference in the function or performance between the dominant and non-dominant limb (Hodges et al., 2011). Inter-limb asymmetry may emerge from long-term training in the same sport (Gray et al., 2016; Hart et al., 2016). There is a growing interest on the topic of inter-limb asymmetry because of its influence on risk for sport injury. The inter-limb asymmetry may potentially place the lower extremities of both sides at an heightened risk of sport injury (Ford et al., 2003). The strong leg may sustain overloading of muscle-tendon components because of increased dependence and prolonged exposure to high force in sport activities, while it may be difficult for the weak leg to manage even average stress and force (Ford et al., 2003). Inter-limb asymmetries in lower-limb strength and power (Knapik et al., 1991), dynamic balance (Plisky et al., 2006; Smith et al., 2015), and muscle flexibility (Knapik et al., 1991) have been associated with increased risk of sport injury in high-school and collegiate athletes.

The literature have suggested the importance of investigating the impact of fatigue on inter-limb asymmetry, due to the potential for asymmetry to become more prominent with fatigue

(Zifchock et al., 2008). The increased inter-limb asymmetry may play a role in the heightened risk of injury under the fatigued state (Bishop, McCauley, et al., 2019). A number of studies have focused on running biomechanics with inconsistent findings reported. Radzak et al. (2017) reported that fatigue amplified the inter-limb asymmetry in knee internal rotation and knee stiffness (increased by 14% and 5.3%, respectively) in running (4 m/s) movement in healthy adults, whereas the inter-limb asymmetry in vertical stiffness and loading rate decreased post fatigue. However, most studies revealed that there was no impact of fatigue on kinematics and kinetics in running movement (Brown et al., 2014; Girard et al., 2017; Girard et al., 2020; Jacques et al., 2020).

Few studies have examined the acute impact of fatigue on inter-limb asymmetry in lower-limb functional performance (jump, dynamic balance, flexibility). The unilateral jump tests have been widely used for assessing inter-limb asymmetry in lower-limb power as the single-leg jumping movements are common in sports and the assessment is time-efficient (Bishop, McCauley, et al., 2019). Findings showed that the inter-limb asymmetry in single-leg CMJ performance increased post fatigue among adolescents (Bromley et al., 2021) and adults (Bishop, McCauley, et al., 2019; Kons, Orssatto, et al., 2020). In addition, the SEBT and its modified version (Y Balance Test) have been widely used to examine the inter-limb asymmetry in dynamic balance and neuromuscular control. However, to the best of our knowledge, the acute effect of fatigue on inter-limb asymmetry in the SEBT or Y Balance Test performance has not been reported. The influence of fatigue on inter-limb asymmetry in lower-limb muscle flexibility which has been reported as a risk factor for sport injury (Knapik et al., 1991) is also not clear.

Current literature has mostly examined athletes in high-school and adulthood years, whereas there is a paucity of research focusing on child athletes. Compared to adult athletes, athletes in childhood-age are more vulnerable to injuries because the immature cartilage and muscles are more susceptible to injuries in sports (Cuff et al., 2010; Radelet et al., 2002). Acute and overuse injuries in the growth cartilage may cause permanent damage to bone growth if they were not treated well (Radelet et al., 2002). Radelet et al. (2002) have reported that the injury rate ranged from 1.0 to 2.3 per 100 athlete exposures in 7-13 y old children in community sports. Examining the inter-limb asymmetry in lower-limb functional performance and the effects of fatigue on this asymmetry is important for the purpose of injury prevention in child athletes, due to the association between inter-limb asymmetry and injury (Knapik et al., 1991; Plisky et al., 2006; Smith et al., 2015). Therefore, the purpose of the present investigation was to examine the acute effects of exercise-induced fatigue on inter-limb asymmetry in jump performance, dynamic balance, and muscle flexibility among child athletes. It was hypothesized that the inter-limb asymmetries would increase at the fatigued state. The present study fits into the framework of translational orthopedics by addressing the gap between basic sciences and clinical sciences (Mediouni, 2019; Mediouni, R. Schlatterer, Madry, Cucchiarini, & Rai, 2018). The potential findings may provide reliable methods (single-leg jump tests, SEBT, and flexibility tests) for practitioners to evaluate the effects of fatigue on inter-limb asymmetry in lower-limb functional performance in child athletes. In addition, generating these findings may contribute to understanding the association between fatigue, inter-limb asymmetry, and sport injury, which may contribute to injury prevention and injury prediction in clinical practice.

7.2 Methods

7.2.1 Participants

A total of 13 elite male taekwondo athletes (height = 144.3 ± 7.8 cm, body mass = 37.6 ± 9.2 kg, age = 9.9 ± 0.8 y, length of training = 3.3 ± 0.9 y) between 9 and 11 y of age were recruited. All participants specialized in taekwondo and had won medals in national level or provincial tournaments. All participants had at least one year of training experience and maintained regular training (3-4 h/d, 4 d/wk) in the preceding 12 months before participation.

7.2.2 Assessments of bilateral asymmetry

Jump performance

Jump tests included the single-leg CMJ, hop, and triple-hop tests. The goal of the single-leg CMJ test was to obtain the maximum jump height of each leg after performing a single-leg countermovement. Participants stood in an upright position with feet positioned shoulder width apart. The hands were placed on hips during the entire movement to reduce the impact of arm movement (Impellizzeri et al., 2007). To start the test, the participant lifted one leg to a self-selected position, and then performed a countermovement followed by a vertical jump. The jump was recorded with an iPhone 6s (Apple, Inc., USA) at 240 Hz. The jump height (cm) was calculated based on the flight time of the jump by identifying the take-off and landing frames using the "My Jump" iPhone application, which has been reported a valid and reliable method (Haynes et al., 2019). Three valid trials were required for each leg. The jump height (cm) for each trial was recorded. The average jump height of the three trials of each leg was used for analysis.

The goal of the single-leg hop and triple-hop test was to obtain the maximum horizontal distance of a hop and three consecutive hops, respectively. Participants started with a unilateral standing position and toes of the supporting leg behind the starting line. For the one hop test, participants were instructed to perform a forward hop as far as possible and land firmly with the same leg. Failure to perform a firm landing was viewed as an invalid trial. The hop distance (cm) from the starting line to the participant's landing heel was measured and recorded. For the triple-hop test, participants were instructed to perform three consecutive forward hops as far as possible using the same leg, with the intention of reducing the floor contact time of the first two landings as much as possible. The landing of the last hop had to be firm. Failure to perform a firm landing at the last hop was viewed as an invalid trial. The total hop distance (cm) from the starting line to the participant's final landing heel was measured and recorded. Three valid trials were required for each leg in each test. The average distance (cm) of the three trials of each leg in each test was used for analysis.

Dynamic Balance

Dynamic balance was measured using a simplified version of the SEBT which is a valid and reliable (ICC = 0.78-0.96) (Hertel et al., 2000) test developed by Gray (1995). The goal of this test was to obtain the maximum reach distance along three directions (Anterior, Posteromedial, and Posterolateral) using the contralateral leg while maintaining a unilateral stance with solid foundation (Coughlan et al., 2012). While standing with a single leg at the convergence of reach direction lines, participants were required to reach as far as possible with the other leg along each of the three directions (in the order of anterior, posteromedial, and posterolateral direction), lightly touching each line using the most distal part of the reaching foot without disrupting the established balance during the entire movement. The point where the most distal part of the foot reached was marked with erasable ink on each direction line. Each participant performed three trials (each trial with three directions) using each leg. Participants took this test barefoot to eliminate the effects of shoes on balance and stability. The trial was viewed as invalid when participants failed to maintain the unilateral stance, moved or lifted the standing foot from the convergence of lines, or failed to return the reaching foot to the original position (Plisky et al., 2006). The greatest reach distance (cm) from the convergence of lines to the point where the most distal part of the foot reached in three trials at each direction in each leg was measured and used for analyses (Plisky et al., 2006).

Hamstrings and gastrocnemius flexibility

Hamstrings and gastrocnemius flexibility was measured using a goniometer. Specific protocols for measurements are reported elsewhere (Witvrouw et al., 2003). The goal of this test was to obtain the maximum range of motion of the hip and ankle joint in a specific position reflecting the flexibility of the hamstrings and gastrocnemius, respectively. The flexibility of the hamstrings was measured with the participant in a supine position on a table (Figure 7.1). The participant lifted the tested leg and keep it straightening with the help from an examiner. The axis of the goniometer was placed at the great trochanter. The stationary arm of the goniometer was placed horizontally at the table, and the moving arm was placed pointing to the lateral epicondyle of the femur. The angle (º) of the maximum flexion at the hip joint was measured. The flexibility of the gastrocnemius was measured with the participant fully extending the knee of the tested leg, and maximally flexing the ankle of the tested leg while maintaining the sole on the floor (Figure 7.2). The stationary arm of the goniometer was placed horizontally to the floor, and the moving arm was placed pointing to the most distal part of the fibula. The angle (º) of the ankle dorsiflexion was measured. When a variation above 5% was found between two trials of each flexibility test, an extra trial was performed. The two most closely related values were recorded and used for analysis.

Figure 7.1 Goniometric measurement of flexibility in the hamstring muscles

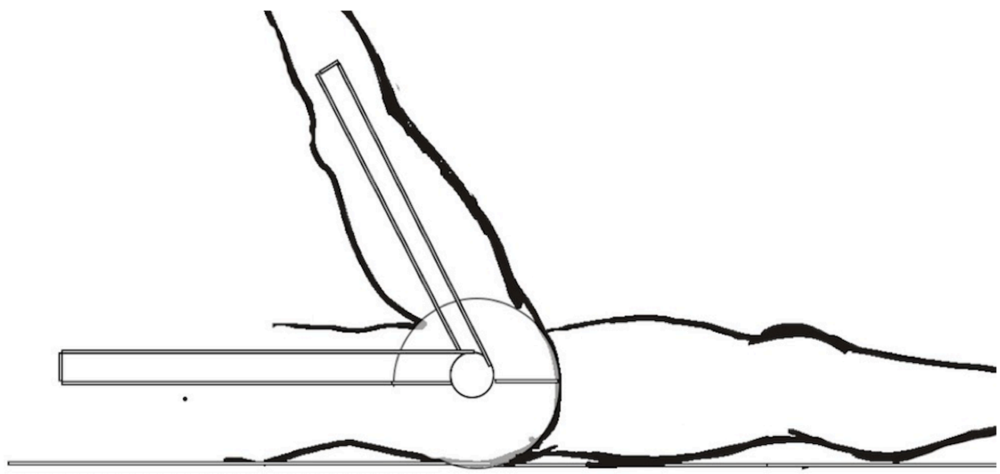
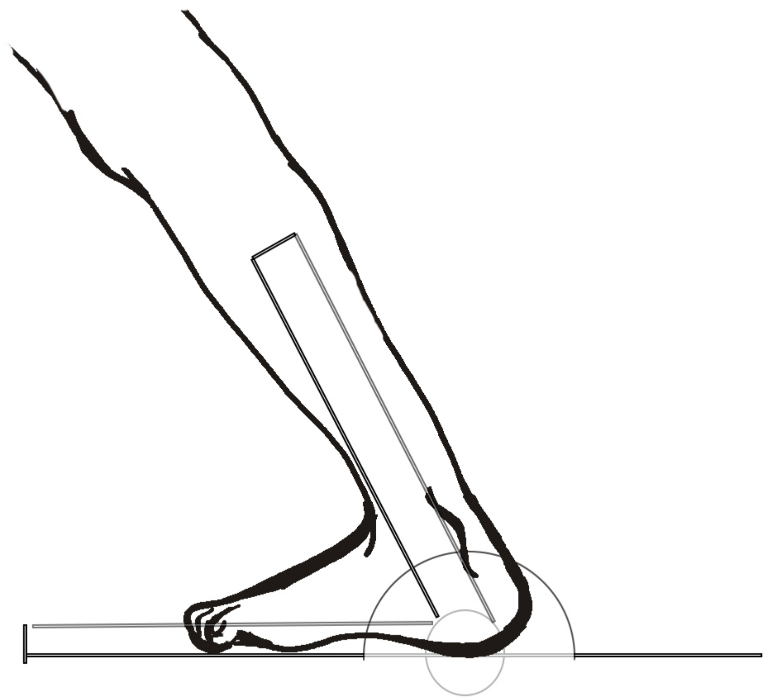


Figure 7.2 Goniometric measurement of flexibility in the gastrocnemius muscles



7.2.3 Fatigue induction

Before performing the fatigue protocol, the participant was asked to perform a broad jump (three trials) to obtain the maximum horizontal distance (cm) achieved at a rested state. The fatigue protocol was modified from previous research (Comyns, Harrison, & Hennessy, 2011; Sant'Ana, Franchini, da Silva, & Diefenthaeler, 2017). First, the participant performed two sets of 30-s consecutive double chop kicks on the punching bag at the maximum frequency, with a break of 30 s between sets. After completing the kicks, the participant received a 30-s rest, followed by performing consecutive frog jumps until volitional exhaustion. This is one set of the fatigue protocol. After one set of fatigue protocol, the participant was asked to test the broad jump again for horizontal distance. The criterion for fatigue was reached when the participant did not attain

90% of his maximum jump (broad jump) distance for three consecutive trials (Comyns et al., 2011; Cortes, Greska, Kollock, Ambegaonkar, & Onate, 2013). If the criterion for fatigue was not reached, the participant started another set of fatigue protocol until reaching the criterion for fatigue.

7.2.4 Procedures

Participants finished all assessments in one visit. First, anthropometric measurements including body height (cm), leg length (cm), and body weight (kg) were taken. Leg length was measured from the anterior superior iliac spine to the most distal aspect of the medial malleolus with participants lying supine on a table. Limb dominance was examined by letting the participant kick a soccer ball, and the limb which the participant preferred for the ball kicking was defined as the dominant leg. In the session, participants then completed stretching and a five-minute jog to warm-up. Participants were then provided with test instructions and received time to practice until they were familiar with each assessment, which included tests measuring jump performance (single-leg CMJ, hop, and triple hop), dynamic balance (SEBT), and muscle flexibility (hamstrings and gastrocnemius). For the SEBT, participants performed at least six practice trials in each direction to account for learning effects (Hertel et al., 2000). Following test familiarization, participants received a rest interval of 5 min.

Testing followed a three-phase approach: 1) testing at a rested state, 2) fatigue induction, and 3) testing at a fatigued state. Testing at a rested state was conducted in the following order: single-leg CMJ, hop, triple hop, SEBT, and flexibility of the hamstrings and gastrocnemius, with a 1-min rest interval between each assessment. At the end of the first phase, participants received a

5-min rest period, followed by the fatigue induction phase until the fatigue criterion was reached. The third phase, testing at a fatigued state, was conducted exactly the same as testing at the rested state except that participants were asked to run continuously between trials with no rest provided between assessments. The starting leg was randomly selected to reduce the order effect.

7.2.5 Data analyses

Dependent variables included the single-leg CMJ height, hop distance, triple-hop distance, the reach distance (normalized to leg length) at each direction (anterior, posteromedial, posterolateral, and the composite score of the three directions) in SEBT, the angles measured in hamstrings and gastrocnemius flexibility tests, the inter-limb asymmetry in performance at the rested and fatigued state in each test, and the variation of performance from the rested to fatigued state (fatigue rate) in each test of each leg. The mean of each dependent variable in jump tests (single-leg CMJ, hop, and triple hop) over the three trials was calculated for each participant. The reach distance in the SEBT was normalized to leg length (leg length%), and the composite reach distance was calculated by averaging the reach distance of the three directions for each leg. The amount of inter-limb asymmetry in each measurement was quantified using an equation modified from previous studies (Sugiyama et al., 2014; Wong et al., 2007): Asymmetry Index = (Stronger Limb − Weaker limb) × 2 / (Stronger Limb + Weaker limb) × 100%. The variation of performance from the rested to fatigued state was calculated as a percentage for each measurement of each leg: (Rested – Fatigued) × 2 / (Rested + Fatigued) × 100%.

7.2.6 Statistical analyses

Descriptive data are shown as mean ± standard deviation. The reliability of each measurement was examined using ICC. Normal distribution and homoscedasticity assumption of the data were examined using the Kolmogorov-Smirnov and Levene's tests, respectively. A two-way repeated measures ANOVA was conducted to examine for difference and the interaction between limb (dominant, non-dominant leg) and state (rested, fatigued state) for each test. Where significant differences were found between limbs or states, paired *t* tests were performed. To compare the inter-limb asymmetry in jump performance (unilateral CMJ, hop, and triple hop) and muscle flexibility (hamstring and gastrocnemius) between the rested and fatigued state, a non-parametric test (Wilcoxon Signed-Rank test) was conducted as the data distribution was not normal. To compare the inter-limb asymmetry in SEBT performance (anterior, posteromedial, posterolateral, and composite reach distance) between the rested and fatigued state, paired *t* tests were performed. The variation of performance from the rested to the fatigued state (fatigue rate) was compared between the dominant and non-dominant leg using a paired *t* test for each test. Effect size was reported using Cohen's d for results in *t* tests (Cohen, 1988), and using the correlation coefficient for results in Wilcoxon Signed-Rank tests ($r = Z/\sqrt{n}$) (Tomczak & Tomczak, 2014). Statistical significance was set a priori at $p < 0.05$. All statistical analyses were conducted using SPSS 23.

7.3 Results

The results of ICC (Table 7.1) showed an excellent reliability of each measurement in the single-leg jump tests, SEBT, and muscle flexibility tests for each leg.

Table 7.1 The intra-class correlation coefficient of each measurement

Tests	Variables	Leg	Rested state		Fatigued state	
			ICC	95% CI	ICC	95% CI
Jumps	CMJ	DL	0.788	0.467-0.929	0.824	0.556-0.942
		NDL	0.888	0.723-0.963	0.945	0.863-0.982
	Hop	DL	0.842	0.606-0.947	0.916	0.744-0.974
		NDL	0.884	0.704-0.962	0.959	0.887-0.987
	Triple Hop	DL	0.930	0.815-0.978	0.866	0.656-0.958
		NDL	0.934	0.830-0.979	0.938	0.835-0.980
SEBT	Anterior RD	DL	0.990	0.970-0.997	0.994	0.973-0.998
		NDL	0.986	0.951-0.996	0.977	0.911-0.993
	Posteromedial RD	DL	0.993	0.947-0.998	0.956	0.870-0.986
		NDL	0.985	0.923-0.996	0.989	0.961-0.997
	Posterolateral RD	DL	0.993	0.959-0.998	0.995	0.986-0.998
		NDL	0.990	0.973-0.997	0.995	0.982-0.999
Flexibility	Hamstring	DL	0.997	0.950-0.999	0.990	0.959-0.997
		NDL	0.989	0.963-0.997	0.997	0.964-0.999
	Gastrocnemius	DL	0.991	0.971-0.997	0.988	0.955-0.996
		NDL	0.991	0.969-0.997	0.990	0.919-0.998

ICC = Intra-class Correlation Coefficient; CI = Confidence Interval; CMJ = Single-leg Countermovement Jump; SEBT = Star Excursion Balance Test; RD = Reach Distance; DL = Dominant Leg; NDL = Non-dominant Leg.

7.3.1 Jump performance

Descriptive statistics for jump tests are presented in Table 7.2. There was a significant main effect of state for single-leg CMJ height ($F_{(1,12)} = 57.880$, $p = 0.000$, $\eta^2 = 0.828$), hop distance ($F_{(1,12)} = 87.557$, $p = 0.000$, $\eta^2 = 0.879$), and triple-hop distance ($F_{(1,12)} = 47.667$, $p = 0.000$, $\eta^2 = 0.799$). For each leg, participants showed significantly better performance at the rested state compared to that at the fatigued state in each test ($p < 0.05$, effect size ≥ 1.148).

Table 7.2 Descriptive statistics for single-leg jump performance

Variables	Limb	Rested state	Fatigued state
CMJ (cm)[a]	DL	14.31 ± 2.05*	12.77 ± 2.02
	NDL	13.95 ± 2.80*	12.29 ± 2.68
Hop (cm)[a]	DL	130.48 ± 12.68*	119.97 ± 12.71
	NDL	125.23 ± 15.06*	117.28 ± 17.58
Triple Hop (cm)[a]	DL	421.82 ± 31.61*	396.42 ± 32.02
	NDL	410.44 ± 39.42*	378.26 ± 44.78

[a] Main effect of state
* Significant difference between the rested and fatigued state.
CMJ = Single-leg Countermovement Jump; DL = Dominant Leg; NDL = Non-dominant Leg.

7.3.2 Dynamic balance

Descriptive statistics for the SEBT are presented in Table 7.3. There was a significant main effect of state for anterior ($F_{(1,12)} = 8.113$, $p = 0.015$, $\eta^2 = 0.403$), posteromedial ($F_{(1,12)} = 8.850$, $p = 0.012$, $\eta^2 = 0.424$), and composite ($F_{(1,12)} = 4.997$, $p = 0.045$, $\eta^2 = 0.294$) reach distance. A significant ($F_{(1,12)} = 6.312$, $p = 0.027$, $\eta^2 = 0.345$) limb by state interaction was shown for the posterolateral direction: the reach distance at the rested state was significantly ($p = 0.005$, effect size = 0.938) greater when establishing the unilateral stance using the dominant leg compared with using the non-dominant leg, while no significant ($p > 0.05$) difference was shown between the two sides at the fatigued state. Results of paired *t* tests showed that posteromedial reach distance at the rested state was significantly greater ($p = 0.023$, effect size = 0.722) than that at the fatigued state when establishing the unilateral stance using the dominant leg, whereas there was no significant difference ($p > 0.05$) between states when using the non-dominant leg.

Table 7.3 Descriptive statistics for Star Excursion Balance Test performance

Variables	Limb	Rested state	Fatigued state
Anterior RD (%)[a]	DL	108.25 ± 12.09*	103.50 ± 10.85
	NDL	108.26 ± 12.14*	103.20 ± 9.61
Posteromedial RD (%)[a]	DL	89.79 ± 10.55*	84.93 ± 12.98
	NDL	89.72 ± 10.93	88.80 ± 10.72
Posterolateral RD (%)[b,c]	DL	82.63 ± 12.56†	78.82 ± 15.97
	NDL	75.91 ± 12.46	77.82 ± 14.20
Composite RD (%)[a]	DL	91.94 ± 10.91	89.08 ± 12.12
	NDL	91.30 ± 10.79	89.94 ± 9.92

[a] Main effect of state.
[b] Main effect of limb.
[c] Significant interaction between limb dominance and state.
* Significant difference between rested and fatigued state.
† Significant difference between the dominant and non-dominant leg.
RD = Reach Distance; DL = Dominant Leg; NDL = Non-dominant Leg.

7.3.3 Muscle flexibility

Descriptive statistics for the performances in lower-limb muscle flexibility tests are presented in Table 7.4. No significant difference was found.

Table 7.4 Descriptive statistics for flexibility test performance

Variables	Limb	Rested state	Fatigued state
Hamstring (º)	DL	67.77 ± 15.58	64.38 ± 21.26
	NDL	68.85 ± 14.67	66.31 ± 18.83
Gastrocnemius (º)	DL	45.54 ± 8.89	48.46 ± 7.47
	NDL	46.62 ± 9.13	47.92 ± 7.94

DL = Dominant Leg; NDL = Non-dominant Leg.

7.3.4 Amount of inter-limb asymmetry and fatigue rate of each leg

The amount of inter-limb asymmetry for each measurement at the rested and fatigued state, and the fatigue rate of each leg in each measurement were shown in Table 7.5. The amount of inter-limb asymmetry in triple-hop distance significantly increased at the fatigued state compared to that at the rested state (Z = -1.992, p = 0.046, effect size = 0.552). The amount of inter-limb asymmetry in anterior reach distance significantly decreased at the fatigued state compared to that at the rested state (p = 0.004, effect size = 0.993). Concerning the fatigue rate, the posterolateral reach distance showed a significantly (p = 0.028, effect size = 0.695) greater decrease, and the composite reach distance showed a tendency (p = 0.056) of greater decrease post fatigue when establishing the unilateral stance using the dominant leg compared with using the non-dominant leg.

Table 7.5 Variation of performance post fatigue (fatigue rate) and inter-limb asymmetry

Variables	Limb	Fatigue rate (%)	State	Asymmetry (%)
Jump performance				
CMJ	DL	11.56 ± 9.33	Rested	8.20 ± 11.97
	NDL	12.79 ± 9.64	Fatigued	12.76 ± 9.48
Hop	DL	8.45 ± 4.52	Rested	6.64 ± 5.99
	NDL	6.91 ± 5.95	Fatigued	9.59 ± 4.79
Triple Hop	DL	6.17 ± 4.82	Rested	5.78 ± 6.41*
	NDL	8.36 ± 6.35	Fatigued	9.69 ± 6.45
SEBT				
Anterior RD	DL	4.40 ± 6.95	Rested	8.36 ± 4.75*
	NDL	4.61 ± 7.36	Fatigued	3.71 ± 3.30
Posteromedial RD	DL	5.96 ± 8.17	Rested	7.44 ± 5.83
	NDL	1.02 ± 6.95	Fatigued	10.67 ± 4.53
Posterolateral RD	DL	5.58 ± 9.62†	Rested	9.97 ± 7.93
	NDL	-2.17 ± 8.04	Fatigued	8.64 ± 6.18
Composite RD	DL	5.13 ± 4.51	Rested	6.06 ± 4.08
	NDL	1.42 ± 3.71	Fatigued	4.03 ± 2.17
Flexibility				
Hamstring	DL	7.48 ± 16.84	Rested	8.32 ± 6.03
	NDL	5.21 ± 19.18	Fatigued	11.33 ± 8.62
Gastrocnemius	DL	-6.92 ± 14.92	Rested	7.85 ± 5.45
	NDL	-3.12 ± 8.30	Fatigued	7.09 ± 6.25

* Significant difference between the rested and fatigued state.
† Significant difference between the dominant and non-dominant leg.
CMJ = Single-leg Countermovement Jump; SEBT, Star Excursion Balance Test; DL = Dominant Leg; NDL = Non-dominant Leg; RD = Reach Distance.

7.4 Discussion

7.4.1 Inter-limb asymmetry in jump performance

We have reported inter-limb asymmetry in single-leg jump performance in child fencing and taekwondo athletes (9-11 y old) in our previous study (Guan et al., 2020). In the present study, no significant difference was found between limbs at the rested or fatigued state for performance in each jumping test based on group means. However, by calculating the amount of inter-limb asymmetry for each participant, we found that the amount of asymmetry of the 13 athletes was 8.20%, 6.64%, and 5.78% at the rested state, and 12.76%, 9.59%, and 9.69% at the fatigued state for the unilateral CMJ height, hop distance, and triple-hop distance, respectively (Table 7.5). This finding implies the importance of assessing and quantifying the inter-limb asymmetry in unilateral jump performance on an individual basis. In fact, the inter-limb asymmetry has been shown with a variable nature as the standard deviation was usually close to even higher than the mean (Bishop, McCauley, et al., 2019), which supports the individual approach when taking inter-limb asymmetry as a measurement in practical application. The amount of inter-limb asymmetry in the present study is similar with those reported in the literature using the same way of calculation to quantify asymmetry: a 9.9 to 16.8% inter-limb asymmetry in peak force and power in bilateral CMJ has been reported in 95% of the collegiate athletes (Bell et al., 2014), and a 6.3% inter-limb asymmetry in running single-leg jump height has been reported in collegiate male basketball athletes (Sugiyama et al., 2014). Age-appropriate comparison in the amount of inter-limb asymmetry is not available due to the paucity of research focusing on children.

Regarding the acute effects of fatigue on jump performance (single-leg CMJ height, hop distance, and triple-hop distance), our results showed a main effect of state (rested vs. fatigued state). The jump performance decreased post fatigue in both legs in all three tests (Table 7.2), indicating that our protocol was appropriate to induce fatigue. By comparing the amount of inter-limb asymmetry between the rested and fatigued state in each test, we found that the asymmetry in triple-hop distance increased post fatigue (Table 7.5). Most studies have reported similar findings: the inter-limb asymmetry in unilateral CMJ height increased post fatigue in active male adults (aged 28.9 ± 5.1 y) (Bishop, McCauley, et al., 2019) and elite adolescent male soccer athletes (aged 17.6 ± 0.5 y) (Bromley et al., 2021); the inter-limb asymmetry in peak force, peak power, and mean power during the unilateral CMJ increased post fatigue in male Judo athletes (aged 22.5 ± 3.6 y) (Kons, Orssatto, et al., 2020). Collectively, these findings indicate that fatigue may amplify the inter-limb asymmetry in jump performance, suggesting the necessity of assessing the inter-limb asymmetry at both the non-fatigued and fatigued state. However, based on our results, the conclusion remains elusive regarding the mechanism of the increased asymmetry in triple-hop distance post fatigue because no significant difference in fatigue rate (the variation of performance from rested to fatigued state) was found between legs (Table 7.5). Jacques et al. (2020) reported that the soleus activation amplitude reduced with fatigue in the dominant leg while not in non-dominant leg when examining the muscle activities using electromyography (EMG) during the running movement, suggesting a higher fatigue rate in the dominant leg. More studies are needed to compare the fatigue rate between limbs when examining the acute impact of fatigue on inter-limb asymmetry in jump performance as direct evidence is still lacking in the literature. Figuring out this problem may help the athletic trainers developing fatigue-resistant programme based on the fatigue response of each leg to improve sport performance and injury prevention for athletes.

7.4.2 Inter-limb asymmetry in dynamic balance

Postural-control assessments, which can be grouped into static and dynamic balance tests, have been used to evaluate risk of injury in sport activities (Gribble et al., 2012; Pollock, 2010). The underlying task of maintaining standing still in static balance tests may not translate necessarily to most sport-movement tasks, in which the balance is dynamically challenged, each time the athletes run, jump, or kick (Hrysomallis et al., 2006). Consequently, the performance in static balance tests may not be translated to identifying injury risk for athletes (Gribble et al., 2012; Pollock, 2010). Although the dynamic balance tests do not exactly replicate the movements in sports, they mimic the demands of sport movements more closely compared with the static balance tests (Gribble et al., 2012). The SEBT offers a simple, reliable, and low-cost method for the assessment of dynamic balance and the inter-limb asymmetry in dynamic balance (Olmsted et al., 2002), and has been used for pre-pubertal (11.66 ± 0.49 y) male taekwondo athletes in previous study (Jlid et al., 2016). It has been reported that an inter-limb asymmetry greater than 4 cm in anterior reach distance in the SEBT indicates increased risk of sport injury in high-school (Plisky et al., 2006) and collegiate athletes (Smith et al., 2015). However, it has been suggested that the reach distance should be normalized to leg length in order to accurately compare the performance between participants (Gribble & Hertel, 2003). We have reported an inter-limb asymmetry ranged from 8.92% to 13.98% in posterolateral reach distance (normalized to leg length) in the SEBT among 9-11 y old male and female fencers and taekwondo athletes in our previous research (Guan et al., 2020). The present study demonstrated similar findings: the 9-11 y old elite male taekwondo athletes showed a significant bilateral difference (Table 7.3) in posterolateral reach distance in SEBT at the rested state (9.97% asymmetry [normalized to leg length], Table 7.5). Future research needs to examine the association between injury risk and inter-limb asymmetry in SEBT performance in child athletes, since there is a lack of research focusing on children.

Research has demonstrated that reach distance in SEBT decreases with fatigue (Gribble, Robinson, Hertel, & Denegar, 2009); however, there is a lack of research examining the acute effects of fatigue on inter-limb asymmetry in SEBT performance. The present study showed a significant interaction between limb (dominant vs. non-dominant) and state (rested vs. fatigued) for posterolateral reach distance, wherein the significant bilateral difference was only shown at the rested state (Table 7.3), implying that the fatigue rate might differ between the dominant and non-dominant leg. The greater decrement in posterolateral reach distance, and a tendency of greater decrement in composite reach distance post fatigue when using the dominant vs. the non-dominant leg for support (Table 7.5) indicated that the SEBT performance decreased more when using the dominant leg for support (non-dominant leg for reaching), implying a reduced ability of neuromuscular control at the fatigued state when establishing a unilateral stance using the dominant leg. Supportively, the posteromedial reach distance significantly decreased post fatigue only when using the dominant leg for support (Table 7.3). Findings in the literature have shown that the reach distance in the SEBT is associated with the kinematics (Armstrong, Brogden, Milner, Norris, & Greig, 2018) and kinetics (Fatahi, Ghasemi, Mongashti Joni, Zolaktaf, & Fatahi, 2016; Gribble & Hertel, 2004) of the supporting leg. Therefore, the greater decrement of reach distance post fatigue when using the dominant leg for support may indicate a higher fatigue rate in the dominant leg. However, it should be noted that the SEBT challenges comprehensive physiological capacities including strength, flexibility, proprioception, and balance (Johnston et al., 2018), and thus the mechanism of the decreased reach distance in SEBT could be complex. Research has reported that the specific postural adaptions caused by taekwondo training are more prominent for the non-dominant leg compared with the dominant leg, due to the fact that taekwondo kicks are more frequently performed using the non-dominant leg for support (Jlid et al., 2016), which may partly explain the mechanism of the higher fatigue rate in the dominant leg in our participants. We suggest future research examine the activity level in lower-limb muscles using EMG during the SEBT, and further explore which leg fatigues more by comparing the variation in muscle-activity levels caused by fatigue when using the dominant vs. non-dominant leg for support, since previous research using EMG for the SEBT only focused on the dominant leg. This will help generating a better understanding for the influence of fatigue on inter-limb asymmetry in SEBT performance.

By quantifying the inter-limb asymmetry, we found that the asymmetry in anterior reach distance significantly decreased post fatigue (Table 7.5), which was conflicting with the results in triple-hop test wherein an increment in inter-limb asymmetry was shown post fatigue. Whilst challenging to explain, this conflict may be attributed to the difference between the jump tests and the SEBT, while the specific mechanism is unclear. Additionally, although we concluded that the fatigue rate might be greater in the dominant leg (in posteromedial and posterolateral reach distance in the SEBT), no significant difference was found between legs in the decrease in anterior reach distance post fatigue and the means were close (4.40% vs. 4.61%, Table 7.5). Thus, the mechanism of the decreased inter-limb asymmetry in anterior reach distance is also unclear. Nevertheless, our findings indicate that the unilateral jump tests and the SEBT should not be used interchangeably when assessing the influence of fatigue on inter-limb asymmetry. Another finding of the present study was that the variations in inter-limb asymmetry post fatigue were inconsistent across the reach directions in SEBT. The muscle activation and kinematic strategy have been reported substantially different across the reach directions in SEBT (Gribble et al., 2012), which may explain the inconsistent results across the reach directions.

An interesting result was that the posterolateral reach distance increased by 2.17% post fatigue in the non-dominant leg (for support) (Table 7.5). Similar results were reported by Armstrong et al. (2018) when examining the effects of fatigue on SEBT performance in university dancers. According to the authors, the increased reach distance might be related to the distinct characteristics of the dance sport as the dancers might have distinct and variable kinematic strategies to maintain or facilitate the SEBT performance under the fatigued condition (Armstrong et al., 2018). In the present study, although the posterolateral reach distance increased with fatigue (2.17%) in the non-dominant leg, this data should be used with caution in practice, due to the standard deviation (8.04%) was much higher than the mean. Furthermore, this result reflects the variable nature of the inter-limb asymmetry, suggesting the importance of assessment on an individual basis when taking the inter-limb asymmetry in SEBT performance as a measurement in practical application.

7.4.3 Inter-limb asymmetry in muscle flexibility

Poor flexibility in hamstrings and gastrocnemius has been associated with increased risks of lower-limb injuries in sports (Hughes, 1985; Silva et al., 2016; Witvrouw et al., 2003). Limited research is avaliable on the association between inter-limb asymmetry in muscle flexibility and injury risk. Knapik et al. (1991) have reported that female collegiate athletes with a 15% or more inter-limb asymmetry in hip extensor sustain more lower-limb injuries. Although this relationship has not been examined in children, practitioners may need to monitor the inter-limb asymmetry in muscle flexibility for child athletes to prevent its potential impact on risk of sport injury. In the present study, the inter-limb asymmetry in hamstrings and gastrocnemius ranged from 7.09 to 11.33% at the rested and fatigued state (Table 7.5). Regarding the effects of fatigue on inter-limb asymmetry in muscle flexibility, there is a paucity of research available from the literature. Our results demonstrated no limb by state interaction for hamstrings or gastrocnemius flexibility, and no main effect of state was shown (Table 7.3), implying that the flexibility of hamstrings and gastrocnemius may not be impacted by fatigue.

7.4.4 Limitations and recommendations

Although participants ran continuously between trials and no rest intervals were permitted between testing at the fatigued state, one cannot rule out that some level of recovery occurred during the SEBT. Therefore, the fatigued state during the muscle flexibility test might be compromised. For the purpose of time, we only examined flexibility in hamstrings and gastrocnemius; therefore, we are unable to provide a global quality of lower-limb muscle flexibility. In addition, the sample size is limited as only 13 participants were included in the present study, while the results of power analysis showed that 33 participants were required. Future research with a larger sample size is warranted to further examine the effects of fatigue on inter-limb asymmetry in lower-limb functional performance.

Data of previous injury was not collected, and thus whether previous injury would impact the inter-limb asymmetry in functional performance and the fatigue response is not clear. Previous research has reported that young soccer players (mean age = 11.2 y) show notably larger inter-limb asymmetry in lateral hop performance compared to that of the younger players (mean age = 9.1 y) (Sannicandro, Quarto, et al., 2014). As participants in the present study aged between 9 and 11 y, there might be an effect of age on the inter-limb asymmetry in jump performance. However, whether this would have an influence on our results regarding the effects of fatigue on inter-limb asymmetry could not be determined in the present study. In addition, the association between inter-limb asymmetry in lower-limb functional performance and anthropometric factors (height, weight) has not been reported, and thus if these factors would impact our results was also unknown. Practitioners also need to be cautious about the skill level (competitive performers) and sex (females vs. males) when utilizing the current findings in youth sport training as participants in the present study are elite male child athletes. Future research may consider including the above-mentioned factors (previous injury, age, height, weight, skill level, and sex) as confounders when examining the impact of fatigue on inter-limb asymmetry in lower-limb functional performance. Findings also need to be extended from taekwondo to other sports.

We mainly discussed inter-limb asymmetry in lower-limb functional performance in the present study; however, the absolute performance was not discussed. When utilizing the measurement of inter-limb asymmetry in lower-limb functional performance for injury prevention, practitioners also need to pay attention to the absolute performance of each side as poor performance on both limbs will be categorized as symmetrical. Further, it is interesting to consider whether great performance could compensate the inter-limb asymmetry, and the potential effect of this on risk of sport injury.

7.5 Conclusions

Fatigue significantly impacts inter-limb asymmetries in jump performance and dynamic balance in child athletes. The variation of inter-limb asymmetry caused by fatigue may be different across tests. Fatigue rates differ between the dominant and non-dominant leg, and further research needs to explore which leg fatigues more. For the purpose of injury prevention, practitioners should consider assessing the inter-limb asymmetry at both the rested and fatigued state for children, and be mindful of the fatigue response of each leg in tests.

Future research should explore the potential factors (e.g., limb dominance [dominant vs. non-dominant leg] and leg length discrepancy) associated with the discrepancy of fatigue rate between limbs. We suggest using EMG to examine the activity level of lower-limb muscles in functional tests, and further explore which leg fatigues more by comparing the variation of muscle-activity levels post fatigue. In addition, future research may consider comparing the present study with numerical simulation, and measuring this fatigue with finite element analysis.

Chapter 8: General Summary and Conclusions

This chapter summarizes the major findings and conclusions derived from the thesis, the strengths and limitations, the implications and applications of these findings, and suggestions for future directions in this area of research.

8.1 Integration and interpretation of major findings

Inter-limb asymmetry in lower-limb functional performance has been suggested as a risk factor for sport injury (Knapik et al., 1991; Smith et al., 2015). Research has widely examined the validity of using inter-limb asymmetry in lower-limb functional performance to predict sport injury (Brumitt et al., 2013; De Blaiser et al., 2021; Fousekis et al., 2011; Fousekis et al., 2012; Smith et al., 2015; Warren et al., 2020). However, a clear statement on the association between inter-limb asymmetry in lower-limb functional performance and sport injury is difficult, due to the highly inconsistent findings. In this dissertation, Chapter 2 and 3 provides a narrative and systematic review, respectively, of the literature pertaining to inter-limb asymmetries and their association with the risk of sport injury. Several major gaps in the literature emerged: 1) inter-limb asymmetry in lower-limb functional performance has been reported in both laterally dominant (Nyström et al., 1990) and non-laterally dominant sports (Maloney, 2019; Newton et al., 2006; Pappas et al., 2015); however, no research has examined the profile of inter-limb asymmetry in child athletes specialized in laterally dominant vs. non-laterally dominant, 2) there is a lack of research examining whether inter-limb asymmetry in lower-limb functional performance can predict sport injury in pediatric-age athletes, 3) when using inter-limb asymmetry in lower-limb functional performance to predict injury, it is unclear whether there is a difference between sexes, and 4) the effects of fatigue on inter-limb asymmetry in lower-limb functional performance have not been examined in pediatric-age athletes.

Consequently, the series of studies contained in this dissertation were conducted to address some of the gaps in the literature. First, a retrospective survey was conducted to examine the effects of lateral dominance in sport (laterally dominant vs. non-laterally dominant sports) on risk of non-contact lower-limb injury in pediatric-age (6-17 y) athletes. Subsequent studies examined the profile of inter-limb asymmetry in lower-limb functional performance in 9-11 y old children specialized in laterally dominant vs. non-laterally dominant sport, and the association between inter-limb asymmetry in lower-limb functional performance and non-contact lower-limb injury in 6-17 y old male and female athletes. The effects of fatigue on inter-limb asymmetry in lower-limb functional performance were also examined in 9-11 y old athletes.

The results of the retrospective survey in Chapter 4 demonstrated greater risk of non-contact lower-limb injury in pediatric-age athletes specialized in laterally dominant vs. non-laterally dominant sport. Left-leg preference, increase in age, training intensity, and training frequency also indicated greater risk of non-contact lower-limb injury in pediatric-age athletes.

In Chapter 5, inter-limb asymmetries in lower-limb functional performance were demonstrated in both laterally dominant (fencing) and non-laterally dominant (taekwondo) sport in 9-11 y old athletes. A limb by sex interaction was shown in single-leg CMJ and SEBT performance; boys were more likely to show inter-limb asymmetry in unilateral jump performance, while girls were more likely to show inter-limb asymmetry in dynamic balance performance, indicating a difference between sexes.

The association between inter-limb asymmetry in lower-limb functional performance and non-contact lower-limb injury in pediatric-age athletes (6-17 y old) was examined in Chapter 6. Approximately 15% of inter-limb asymmetry (calculated using equation: [Stronger Limb − Weaker limb] × 2 / [Stronger Limb + Weaker limb] × 100 [%]) in single-leg CMJ height can be used as a cut-off value to predict non-contact lower-limb injury in pediatric-age male athletes. The boys with ≥15.28% inter-limb asymmetry in single-leg CMJ height showed greater risk of non-contact lower-limb injury compared with those with <15.28% asymmetry. There is a difference between sexes when using inter-limb asymmetries (as a continuous variable) in unilateral jump performance to predict injury in pediatric-age athletes. The increase of inter-limb asymmetries in single-leg CMJ height, hop distance, and triple hop distance indicated greater risk of non-contact lower-limb injury in pediatric-age male athletes, while only the inter-limb asymmetry in single-leg CMJ height was associated with non-contact lower-limb injury in pediatric-age female athletes. Inter-limb asymmetries in SEBT performance were not associated with non-contact lower-limb injury in pediatric-age athletes.

The effects of fatigue on inter-limb asymmetry in lower-limb functional performance in 9-11 y old male athletes were reported in Chapter 7. Inter-limb asymmetry in triple-hop distance increased with fatigue, whereas inter-limb asymmetry in anterior reach distance in the SEBT decreased with fatigue.

8.2 Strengths and limitations

8.2.1 Strengths

The series of studies in this thesis were conducted in a logical sequence with the order of a retrospective survey, a cross-sectional study examining the profile of inter-limb asymmetry, a prospective study investigating whether inter-limb asymmetry can predict injury, and a cross-sectional study to examine the effects of fatigue on inter-limb asymmetry, based on pediatric-age athletes. Focusing on pediatric-age athletes, this is the first study to examine inter-limb asymmetry in lower-limb functional performance in laterally dominant vs. non-laterally dominant sport. This is also the first prospective study to examine the association between inter-limb asymmetry in lower-limb functional performance and injury in pediatric-age athletes with a large sample size with each sex; the difference between sexes is also addressed, which has been neglected in previous studies. The findings of the prospective study could stimulate further research and impact on the application of screening test for pediatric-age athletes aimed at reducing injury risk. Moreover, these findings provide a foundation for further investigations evaluating whether correction of the asymmetries can prevent injury.

8.2.2 Limitations

There are a few limitations that warrant attention. For instance, data of previous injury and exposure time to sport training were not collected; therefore, the findings of this series of investigations did not control for previous injury and exposure time. Moreover, the athletes in the prospective study were not stratified based on age, and whether age and different stages of development impacted on the results was not clear. Another limitation is the potential for reporting bias in the prospective study due to the fact that some of the injuries were reported by coaches and were not verified by medical staff. A further limitation is the inability to include multiple sport disciplines when examining inter-limb asymmetry and the association between inter-limb asymmetry and non-contact lower-limb injury. In addition, we did not report the direction of asymmetry as the difference in asymmetry direction between tests would not affect related findings; within the same test, it is not reasonable to see a dramatic difference in asymmetry direction if the participants perform well in each valid trial.

8.3 Implications and applications

The limb by sex interaction in single-leg CMJ and SEBT performance indicated the necessity of separating boys and girls when assessing inter-limb asymmetries in jump performance and dynamic balance for children. Our findings also implied that it is necessary to examine inter-limb asymmetry in pediatric-age athletes in both laterally dominant and non-laterally dominant sports.

Inter-limb asymmetries in unilateral jump performance (single-leg CMJ height, hop distance, and triple-hop distance) can be utilized to evaluate the risk of non-contact lower-limb injury in pediatric-age athletes; practitioners should pay attention to the difference between sexes. With the utilization of the inter-limb asymmetries in unilateral jump tests for injury prediction, at risk athletes can be identified and monitored more closely, with the potential for preventive intervention. Inter-limb asymmetry in reach distance in the SEBT (or the Y Balance Test) is not recommended for injury prediction in pediatric-age athletes in clinical application, because no association between this asymmetry and injury was shown in the present investigation, and most studies to date did not demonstrate a strong association with predicting sport injury. In addition, child athletes (9-11 y old) should avoid frequently training with a fatigued state, due to the findings showing that inter-limb asymmetries in lower-limb power may increase with fatigue, which may increase the risk of lower-limb injury.

To evaluate and reduce the risk of sport injury in pediatric-age athletes, the present findings should be used in combination with the individual basis of each athlete. In practical application, it is important for the coaches and athletic trainers to consider all potential factors (training information [e.g., frequency, intensity, duration, and length of training], previous injury, age, sex, physical fitness, asymmetry, etc.) when predicting sport injury for each athlete, instead of exclusively focusing on one aspect to draw a conclusion. In addition, we suggest the coaches and athletic trainers continuously monitor and evaluate the potential risk factors (of sport injury) for youth athletes throughout the season, instead of just testing once pre-season.

8.4 Future research

Although the present investigation demonstrated inter-limb asymmetries in lower-limb functional performance in child athletes (9-11 y old) in both laterally dominant (fencing) and non-laterally dominant (taekwondo) sports, future research with a large sample in a wide spectrum of ages from multiple sports is required to further examine the effects of lateral dominance in sport (laterally vs. non-laterally dominant sport) on inter-limb asymmetry in lower-limb functional performance. Future research should also explore whether inter-limb asymmetry in unilateral jump performance can predict non-contact lower-limb injury in sports other than taekwondo. Future research may also consider to further investigate the association between inter-limb asymmetry and sport injury by stratifying the young athletes based on age. It is also important for future research to evaluate whether correction of asymmetry between lower limbs can prevent injury in pediatric-age athletes. In addition, future research may consider comparing the rate and pattern of injury in the dominant vs. non-dominant leg, and explore the potential mechanism if a difference was found. Concerning the effects of fatigue on inter-limb asymmetries in lower-limb functional performance, future research should further examine the difference in fatigue rate between the dominant and non-dominant leg, and the potential mechanism.

References

Aagaard, P., Simonsen, E., Trolle, M., Bangsbo, J., & Klausen, K. (1995). Isokinetic hamstring/quadriceps strength ratio: influence from joint angular velocity, gravity correction and contraction mode. *Acta Physiologica Scandinavica, 154*(4), 421-427.

Aagaard, P., Simonsen, E. B., Magnusson, S. P., Larsson, B., & Dyhre-Poulsen, P. (1998). A new concept for isokinetic hamstring: quadriceps muscle strength ratio. *The American journal of sports medicine, 26*(2), 231-237.

Agel, J., Arendt, E. A., & Bershadsky, B. (2005). Anterior cruciate ligament injury in national collegiate athletic association basketball and soccer: a 13-year review. *The American journal of sports medicine, 33*(4), 524-531.

An, W. W., Wong, V., & Cheung, R. T. (2015). Lower limb reaction force asymmetry in rowers with and without a history of back injury. *Sports biomechanics, 14*(4), 375-383.

Armstrong, N., Barker, A. R., & McManus, A. M. (2015). Muscle metabolism changes with age and maturation: How do they relate to youth sport performance? *British Journal of Sports Medicine, 49*(13), 860-864.

Armstrong, R., Brogden, C. M., Milner, D., Norris, D., & Greig, M. (2018). The influence of fatigue on star excursion balance test performance in dancers. *Journal of Dance Medicine & Science, 22*(3), 142-147.

Atkins, S. J., Bentley, I., Hurst, H. T., Sinclair, J. K., & Hesketh, C. (2016). The presence of bilateral imbalance of the lower limbs in elite youth soccer players of different ages. *The Journal of Strength & Conditioning Research, 30*(4), 1007-1013.

Bampouras, T. M., & Dewhurst, S. (2018). A comparison of bilateral muscular imbalance ratio calculations using functional tests. *Journal of Strength & Conditioning Research, 32*(8), 2216-2220.

Bampouras, T. M., & Dewhurst, S. (2018). A comparison of bilateral muscular imbalance ratio calculations using functional tests. *The Journal of Strength & Conditioning Research, 32*(8), 2216-2220.

Barber, S. D., Noyes, F. R., Mangine, R. E., McCloskey, J., & Hartman, W. (1990). Quantitative assessment of functional limitations in normal and anterior cruciate ligament-deficient knees. *Clinical Orthopaedics and Related Research, 255*, 204-214.

Barber-Westin, S. D., & Noyes, F. R. (2017). Effect of fatigue protocols on lower limb neuromuscular function and implications for anterior cruciate ligament injury prevention training: a systematic review. *The American journal of sports medicine, 45*(14), 3388-3396.

Barbieri, F. A., Gobbi, L. T. B., Santiago, P. R. P., & Cunha, S. A. (2015). Dominant – non-dominant asymmetry of kicking a stationary and rolling ball in a futsal context. *Journal of Sports Sciences, 33*(13), 1411-1419.

Bastos, F. N., Vanderlei, F. M., Vanderlei, L. C. M., Júnior, J. N., & Pastre, C. M. (2013). Investigation of characteristics and risk factors of sports injuries in young soccer players: a retrospective study. *International Archives of Medicine, 6*(1), 14.

Batista, A., Garganta, R., & Ávila-Carvalho, L. (2019). Flexibility and functional asymmetry in rhythmic gymnastics. *Athens Journal Os Sports, 6*(2), 77-94.

Bell, D. R., Pennuto, A. P., & Trigsted, S. M. (2016). The effect of exertion and sex on vertical ground reaction force variables and landing mechanics. *Journal of Strength and Conditioning Research, 30*(6), 1661-1669.

Bell, D. R., Pennuto, A. P., & Trigsted, S. M. (2016). The effect of exertion and sex on vertical ground reaction force variables and landing mechanics. *Journal of Strength & Conditioning Research (Lippincott Williams & Wilkins), 30*(6), 1661-1669.

Bell, D. R., Sanfilippo, J. L., Binkley, N., & Heiderscheit, B. C. (2014). Lean mass asymmetry influences force and power asymmetry during jumping in collegiate athletes. *Journal of Strength and Conditioning Research, 28*(4), 884-891.

Benjanuvatra, N., Lay, B. S., Alderson, J. A., & Blanksby, B. A. (2013). Comparison of ground reaction force asymmetry in one-and two-legged countermovement jumps. *The Journal of Strength & Conditioning Research, 27*(10), 2700-2707.

Beshay, N., Lam, P. H., & Murrell, G. A. (2011). Assessing the reliability of shoulder strength measurement: hand-held versus fixed dynamometry. *Shoulder & Elbow, 3*(4), 244-251.

Bijur, P. E., Trumble, A., Harel, Y., Overpeck, M. D., Jones, D., & Scheidt, P. C. (1995). Sports and recreation injuries in US children and adolescents. *Archives of Pediatrics and Adolescent Medicine, 149*(9), 1009-1016.

Bini, R. R., & Hume, P. (2015). Relationship between pedal force asymmetry and performance in cycling. *Journal of Sports Medicine and Physical Fitness, 55*(9), 892-898.

Bishop, C., Brashill, C., Abbott, W., Read, P., Lake, J. P., & Turner, A. (2019). Jumping asymmetries are associated with speed, change of direction speed, and jump performance in elite academy soccer players. *Journal of Strength and Conditioning Research, 35*(7), 1841-1847.

Bishop, C., McCauley, W., Read, P., Gonzalo-Skok, O., Lake, J. P., & Turner, A. (2019). Acute effects of repeated sprints on interlimb asymmetries during unilateral jumping. *Journal of Strength and Conditioning Research, 35*(8), 2127-2132.

Bishop, C., Pereira, L. A., Reis, V. P., Read, P., Turner, A. N., & Loturco, I. (2020). Comparing the magnitude and direction of asymmetry during the squat, countermovement and drop jump tests in elite youth female soccer players. *Journal of Sports Sciences, 38*(11-12), 1296-1303.

Bishop, C., Read, P., Chavda, S., & Turner, A. (2016). Asymmetries of the lower limb: The calculation conundrum in strength training and conditioning. *Strength & Conditioning Journal, 38*(6), 27-32.

Bishop, C., Read, P., Lake, J., Chavda, S., & Turner, A. (2018). Inter-limb asymmetries: understanding how to calculate differences from bilateral and unilateral tests. *Strength & Conditioning Journal, 40*(4), 1-6.

Bishop, C., Read, P., McCubbine, J., & Turner, A. N. (2021). Vertical and horizontal asymmetries are related to slower sprinting and jump performance in elite youth female soccer players. *Journal of Strength and Conditioning Research, 35*(1), 56-63.

Bishop, C., Turner, A., & Read, P. (2018). Effects of inter-limb asymmetries on physical and sports performance: a systematic review. *Journal of Sports Sciences, 36*(10), 1135-1144.

Black, G. M., Gabbett, T. J., Cole, M. H., & Naughton, G. (2016). Monitoring workload in throwing-dominant sports: a systematic review. *Sports Medicine, 46*(10), 1503-1516.

Bolgla, L. A., & Keskula, D. R. (1997). Reliability of lower extremity functional performance tests. *Journal of Orthopaedic and Sports Physical Therapy, 26*(3), 138-142.

Bressel, E., Yonker, J. C., Kras, J., & Heath, E. M. (2007). Comparison of static and dynamic balance in female collegiate soccer, basketball, and gymnastics athletes. *Journal of Athletic Training, 42*(1), 42-46.

Brito, J., Rebelo, A., Soares, J. M., Seabra, A., Krustrup, P., & Malina, R. M. (2011). Injuries in youth soccer during the preseason. *Clinical Journal of Sport Medicine, 21*(3), 259-260.

Bromley, T., Turner, A., Read, P., Lake, J., Maloney, S., Chavda, S., & Bishop, C. (2021). Effects of a competitive soccer match on jump performance and interlimb asymmetries in elite academy soccer players. *The Journal of Strength & Conditioning Research, 35*(6), 1707-1714.

Brophy, R., Chiaia, T., Maschi, R., Dodson, C., Oh, L., Lyman, S., . . . Williams, R. (2009). The core and hip in soccer athletes compared by gender. *International Journal of Sports Medicine, 30*(9), 663-667.

Brown, A. M., Zifchock, R. A., & Hillstrom, H. J. (2014). The effects of limb dominance and fatigue on running biomechanics. *Gait and Posture, 39*(3), 915-919.

Brumitt, J., Heiderscheit, B. C., Manske, R. C., Niemuth, P. E., & Rauh, M. J. (2013). Lower Extremity Functional Tests and Risk of Injury in Division III Collegiate Athletes. *International Journal of Sports Physical Therapy, 8*(3), 216-227.

Brumitt, J., Mattocks, A., Loew, J., & Lentz, P. (2020). Preseason Functional Performance Test Measures Are Associated With Injury in Female College Volleyball Players. *Journal of sport rehabilitation, 29*(3), 320-325.

Brumitt, J., Nelson, K., Duey, D., Jeppson, M., & Hammer, L. (2019). Preseason Y Balance Test Scores are not associated with noncontact time-loss lower quadrant injury in male collegiate basketball players. *Sports, 7*(1), 4.

Brumitt, J., Sikkema, J., Mair, S., Zita, C., Wilson, V., & Petersen, J. (2020). Preseason Y Balance Test Scores are Not Associated With a Lower Quadrant Sports Injury in a Heterogeneous Population of Division III Collegiate Athletes. *International Journal of Athletic Therapy & Training, 25*(2), 68-75.

Buschang, P., Malina, R., & Little, B. (1986). Linear growth of Zapotec schoolchildren: growth status and yearly velocity for leg length and sitting height. *Annals of Human Biology, 13*(3), 225-234.

Butler, R. J., Lehr, M. E., Fink, M. L., Kiesel, K. B., & Plisky, P. J. (2013). Dynamic balance performance and noncontact lower extremity injury in college football players: an initial study. *Sports health, 5*(5), 417-422.

Calatayud, J., Borreani, S., Colado, J. C., Martin, F., & Flandez, J. (2014). Test-retest reliability of the star excursion balance test in primary school children. *The Physician and sportsmedicine, 42*(4), 120-124.

Castanharo, R., Da Luz, B. S., Bitar, A. C., D’Elia, C. O., Castropil, W., & Duarte, M. (2011). Males still have limb asymmetries in multijoint movement tasks more than 2 years following anterior cruciate ligament reconstruction. *Journal of Orthopaedic Science, 16*(5), 531-535.

Cejudo, A., de Baranda, P. S., Ayala, F., & Santonja, F. (2015). Test-retest reliability of seven common clinical tests for assessing lower extremity muscle flexibility in futsal and handball players. *Physical Therapy in Sport, 16*(2), 107-113.

Cejudo, A., Moreno-Alcaraz, V. J., Izzo, R., Robles-Palazón, F. J., Sainz de Baranda, P., & Santonja-Medina, F. (2020). Flexibility in Spanish elite inline hockey players: Profile, sex, tightness and asymmetry. *International Journal of Environmental Research and Public Health, 17*(9), 3295.

Ceroni, D., Martin, X. E., Delhumeau, C., & Farpour-Lambert, N. J. (2012). Bilateral and gender differences during single-legged vertical jump performance in healthy teenagers. *The Journal of Strength & Conditioning Research, 26*(2), 452-457.

Chimera, N. J., Smith, C. A., & Warren, M. (2015). Injury history, sex, and performance on the functional movement screen and Y balance test. *Journal of Athletic Training, 50*(5), 475-485.

Clark, R. A., Bell, S. W., Feller, J. A., Whitehead, T. S., & Webster, K. E. (2017). Standing balance and inter-limb balance asymmetry at one year post primary anterior cruciate ligament reconstruction: sex differences in a cohort study of 414 patients. *Gait and Posture, 52*, 318-324.

Cohen, J. (1988). Statistical Power Analysis for the Behavioral Sciences. 2nd edn. Hillsdale, NJ: Lawrence Erlbaum Associates.

Comyns, T. M., Harrison, A. J., & Hennessy, L. K. (2011). An investigation into the recovery process of a maximum stretch-shortening cycle fatigue protocol on drop and rebound jumps. *The Journal of Strength & Conditioning Research, 25*(8), 2177-2184.

Cortes, N., Greska, E., Kollock, R., Ambegaonkar, J., & Onate, J. A. (2013). Changes in lower extremity biomechanics due to a short-term fatigue protocol. *Journal of Athletic Training, 48*(3), 306-313.

Coughlan, G. F., Fullam, K., Delahunt, E., Gissane, C., & Caulfield, B. M. (2012). A comparison between performance on selected directions of the star excursion balance test and the Y balance test. *Journal of Athletic Training, 47*(4), 366-371.

Cuff, S., Loud, K., & O'riordan, M. A. (2010). Overuse injuries in high school athletes. *Clinical Pediatrics, 49*(8), 731-736.

Daneshjoo, A., Rahnama, N., Mokhtar, A. H., & Yusof, A. (2013). Bilateral and unilateral asymmetries of isokinetic strength and flexibility in male young professional soccer players. *Journal of Human Kinetics, 36*(1), 45-53.

De Blaiser, C., Roosen, P., Willems, T., De Bleecker, C., Vermeulen, S., Danneels, L., & De Ridder, R. (2021). The role of core stability in the development of non-contact acute lower extremity injuries in an athletic population: A prospective study. *Physical Therapy in Sport, 47*, 165-172.

Di Stasi, S., Hartigan, E. H., & Snyder-Mackler, L. (2015). Sex-specific gait adaptations prior to and up to 6 months after anterior cruciate ligament reconstruction. *Journal of Orthopaedic and Sports Physical Therapy, 45*(3), 207-214.

Di Stasi, S. L., & Snyder-Mackler, L. (2012). The effects of neuromuscular training on the gait patterns of ACL-deficient men and women. *Clinical Biomechanics, 27*(4), 360-365.

Dick, R., Putukian, M., Agel, J., Evans, T. A., & Marshall, S. W. (2007). Descriptive epidemiology of collegiate women's soccer injuries: National Collegiate Athletic Association Injury Surveillance System, 1988 – 1989 through 2002 – 2003. *Journal of Athletic Training, 42*(2), 278-285.

Eagle, S. R., Keenan, K. A., Connaboy, C., Wohleber, M., Simonson, A., & Nindl, B. C. (2019). Bilateral quadriceps strength asymmetry is associated with previous knee injury in military special tactics operators. *The Journal of Strength & Conditioning Research, 33*(1), 89-94.

Ekstrand, J., Hägglund, M., & Waldén, M. (2011). Injury incidence and injury patterns in professional football: the UEFA injury study. *British Journal of Sports Medicine, 45*(7), 553-558.

Emery, C., & Tyreman, H. (2009). Sport participation, sport injury, risk factors and sport safety practices in Calgary and area junior high schools. *Paediatrics & Child Health, 14*(7), 439-444.

Emery, C. A. (2003). Risk factors for injury in child and adolescent sport: a systematic review of the literature. *Clinical Journal of Sport Medicine, 13*(4), 256-268.

Emery, C. A., Meeuwisse, W. H., & Hartmann, S. E. (2005). Evaluation of risk factors for injury in adolescent soccer: implementation and validation of an injury surveillance system. *The American journal of sports medicine, 33*(12), 1882-1891.

Emery, C. A., Meeuwisse, W. H., & McAllister, J. R. (2006). Survey of sport participation and sport injury in Calgary and area high schools. *Clinical Journal of Sport Medicine, 16*(1), 20-26.

Fatahi, M., Ghasemi, G. A., Mongashti Joni, Y., Zolaktaf, V., & Fatahi, F. (2016). The effect of lower extremity muscle fatigue on dynamic postural control analyzed by electromyography. *Physical Treatments, 6*(1), 37-50.

Ford, K. R., Myer, G. D., & Hewett, T. E. (2003). Valgus knee motion during landing in high school female and male basketball players. *Medicine and Science in Sports and Exercise, 35*(10), 1745-1750.

Fort-Vanmeerhaeghe, A., Gual, G., Romero-Rodriguez, D., & Unnitha, V. (2016). Lower limb neuromuscular asymmetry in volleyball and basketball players. *Journal of Human Kinetics, 50*(1), 135-143.

Fort-Vanmeerhaeghe, A., Mila-Villarroel, R., Pujol-Marzo, M., Arboix-Alio, J., & Bishop, C. (2020). Higher Vertical Jumping Asymmetries and Lower Physical Performance are Indicators of Increased Injury Incidence in Youth Team-Sport Athletes. *Journal of Strength and Conditioning Research, Publish ahead of print*.

Fousekis, K., Tsepis, E., Poulmedis, P., Athanasopoulos, S., & Vagenas, G. (2011). Intrinsic risk factors of non-contact quadriceps and hamstring strains in soccer: a prospective study of 100 professional players. *British Journal of Sports Medicine, 45*(8), 709-714.

Fousekis, K., Tsepis, E., & Vagenas, G. (2012). Intrinsic Risk Factors of Noncontact Ankle Sprains in Soccer: A Prospective Study on 100 Professional Players. *American Journal of Sports Medicine, 40*(8), 1842-1850.

Frutuoso, A. S., Diefenthaeler, F., Vaz, M. A., & de la Rocha Freitas, C. (2016). Lower limb asymmetries in rhythmic gymnastics athletes. *International Journal of Sports Physical Therapy, 11*(1), 34-43.

Geuze, R. H. (2003). Static balance and developmental coordination disorder. *Human Movement Science, 22*(4-5), 527-548.

Gilgen-Ammann, R., Taube, W., & Wyss, T. (2017). Gait asymmetry during 400-to 1000-m high-intensity track running in relation to injury history. *International Journal of Sports Physiology and Performance, 12*(s2), S2157-S2160.

Girard, O., Brocherie, F., Morin, J. B., & Millet, G. P. (2017). Lower limb mechanical asymmetry during repeated treadmill sprints. *Human Movement Science, 52*, 203-214.

Girard, O., Racinais, S., Couderc, A., Morin, J.-B., Ryu, J. H., Piscione, J., & Brocherie, F. (2020). Asymmetries during repeated treadmill sprints in elite female Rugby Sevens players. *Sports Biomechanics, Publish ahead of print*.

Gleim, G. W., & McHugh, M. P. (1997). Flexibility and its effects on sports injury and performance. *Sports Medicine, 24*(5), 289-299.

Gonell, A. C., Romero, J. A. P., & Soler, L. M. (2015). Relationship between the Y balance test scores and soft tissue injury incidence in a soccer team. *International Journal of Sports Physical Therapy, 10*(7), 955-966.

Gorman, P. P., Butler, R. J., Rauh, M. J., Kiesel, K., & Plisky, P. J. (2012). Differences in dynamic balance scores in one sport versus multiple sport high school athletes. *International Journal of Sports Physical Therapy, 7*(2), 148.

Graham, C. J., & Cleveland, E. (1995). Left-handedness as an injury risk factor in adolescents. *Journal of Adolescent Health, 16*(1), 50-52.

Gray, G. W. (1995). *Lower extremity functional profile*. Adrian, MI: Wynn Marketing, Incorporated.

Gray, J., Aginsky, K. D., Derman, W., Vaughan, C. L., & Hodges, P. W. (2016). Symmetry, not asymmetry, of abdominal muscle morphology is associated with low back pain in cricket fast bowlers. *Journal of Science and Medicine in Sport, 19*(3), 222-226.

Gribble, P. A., & Hertel, J. (2003). Considerations for normalizing measures of the Star Excursion Balance Test. *Measurement in physical education and exercise science, 7*(2), 89-100.

Gribble, P. A., & Hertel, J. (2004). Effect of lower-extremity muscle fatigue on postural control. *Archives of Physical Medicine and Rehabilitation, 85*(4), 589-592.

Gribble, P. A., Hertel, J., & Plisky, P. (2012). Using the Star Excursion Balance Test to assess dynamic postural-control deficits and outcomes in lower extremity injury: a literature and systematic review. *Journal of Athletic Training, 47*(3), 339-357.

Gribble, P. A., Robinson, R. H., Hertel, J., & Denegar, C. R. (2009). The effects of gender and fatigue on dynamic postural control. *Journal of sport rehabilitation, 18*(2), 240-257.

Grobbelaar, H. W. (2003). *Upper body anthropometrical differences amongst participants of asymmetrical (fast bowlers in cricket) and symmetrical (crawl stroke swimmers) sport and sedentary individuals in South Africa.* (M.Sc.), Potchefstroom University, Potchefstroom. Retrieved from http://hdl.handle.net/10394/228

Guan, Y., Bredin, S., Taunton, J., Jiang, Q., Wu, L., Kaufman, K., . . . Warburton, D. (2020). Bilateral difference between lower limbs in children practicing laterally dominant vs. non-laterally dominant sports. *European Journal of Sport Science, Publish ahead of print*.

Guan, Y., Guo, L., Wu, N., Zhang, L., & Warburton, D. E. (2018). Biomechanical insights into the determinants of speed in the fencing lunge. *European Journal of Sport Science, 18*(2), 201-208.

Hart, N. H., Nimphius, S., Weber, J., Spiteri, T., Rantalainen, T., Dobbin, M., & Newton, R. (2016). Musculoskeletal asymmetry in football athletes: a product of limb function over time. *Medicine and Science in Sports and Exercise, 48*(7), 1379-1387.

Hartley, E. M., Hoch, M. C., & Boling, M. C. (2018). Y-balance test performance and BMI are associated with ankle sprain injury in collegiate male athletes. *Journal of Science and Medicine in Sport, 21*(7), 676-680.

Haynes, T., Bishop, C., Antrobus, M., & Brazier, J. (2019). The validity and reliability of the my jump 2 app for measuring the reactive strength index and drop jump performance. *The Journal of sports medicine and physical fitness, 59*(2), 253-258.

Haywood, K., & Getchell, N. (2020). *Life span motor development* (Seventh ed.). Champaign, IL: Human Kinetics.

Heil, J., Loffing, F., & Büsch, D. (2020). The Influence of Exercise-Induced Fatigue on Inter-Limb Asymmetries: a Systematic Review. *Sports Medicine-Open, 6*(1), 39.

Hertel, J. (2008). Sensorimotor deficits with ankle sprains and chronic ankle instability. *Clinics in Sports Medicine, 27*(3), 353-370.

Hertel, J., Braham, R. A., Hale, S. A., & Olmsted-Kramer, L. C. (2006). Simplifying the star excursion balance test: analyses of subjects with and without chronic ankle instability. *Journal of Orthopaedic and Sports Physical Therapy, 36*(3), 131-137.

Hertel, J., Miller, S. J., & Denegar, C. R. (2000). Intratester and intertester reliability during the Star Excursion Balance Tests. *Journal of sport rehabilitation, 9*(2), 104-116.

Hietamo, J., Pasanen, K., Leppänen, M., Steffen, K., Kannus, P., Heinonen, A., . . . Parkkari, J. (2021). Association between lower extremity muscle strength and acute ankle injury in youth team-sports athletes. *Physical Therapy in Sport, 48*, 188-195.

Hodges, S. J., Patrick, R. J., & Reiser, R. F. (2011). Effects of fatigue on bilateral ground reaction force asymmetries during the squat exercise. *The Journal of Strength & Conditioning Research, 25*(11), 3107-3117.

Hootman, J. M., Dick, R., & Agel, J. (2007). Epidemiology of collegiate injuries for 15 sports: summary and recommendations for injury prevention initiatives. *Journal of Athletic Training, 42*(2), 311-319.

Hrysomallis, C., McLaughlin, P., & Goodman, C. (2006). Relationship between static and dynamic balance tests among elite Australian Footballers. *Journal of Science and Medicine in Sport, 9*(4), 288-291.

Hughes, L. Y. (1985). Biomechanical analysis of the foot and ankle for predisposition to developing stress fractures. *Journal of Orthopaedic and Sports Physical Therapy, 7*(3), 96-101.

Impellizzeri, F. M., Rampinini, E., Maffiuletti, N., & Marcora, S. M. (2007). A vertical jump force test for assessing bilateral strength asymmetry in athletes. *Medicine and Science in Sports and Exercise, 39*(11), 2044-2050.

Izovska, J., Mikic, M., Dragijsky, M., Zahalka, F., Bujnovsky, D., & Hank, M. (2019). Pre-season bilateral strength asymmetries of professional soccer players and relationship with non-contact injury of lower limb in the season. *Sport Mont, 17*(2), 107-110.

Jacques, T., Bini, R., & Arndt, A. (2020). Running after cycling induces inter-limb differences in muscle activation but not in kinetics or kinematics. *Journal of Sports Sciences, 39*(2), 154-160.

Jeong, H. S., Ha, S., Jeong, D. H., O'Sullivan, D. M., & Lee, S. Y. (2021). Injury and illness in World Taekwondo Junior Athletes: an epidemiological study. *International Journal of Environmental Research and Public Health, 18*(4), 2134.

Jlid, M. C., Maffulli, N., Souissi, N., Chelly, M. S., & Paillard, T. (2016). Pre-pubertal males practising Taekwondo exhibit favourable postural and neuromuscular performance. *BMC Sports Science, Medicine and Rehabilitation, 8*, 16.

Johnston, W., Dolan, K., Reid, N., Coughlan, G. F., & Caulfield, B. (2018). Investigating the effects of maximal anaerobic fatigue on dynamic postural control using the Y-Balance Test. *Journal of Science and Medicine in Sport, 21*(1), 103-108.

Jordan, M., Aagaard, P., & Herzog, W. (2015). Lower limb asymmetry in mechanical muscle function: A comparison between ski racers with and without ACL reconstruction. *Scandinavian Journal of Medicine and Science in Sports, 25*(3), e301-e309.

Kannus, P. (1988). Ratio of hamstring to quadriceps femoris muscles' strength in the anterior cruciate ligament insufficient knee: relationship to long-term recovery. *Physical Therapy, 68*(6), 961-965.

King, D. (2006). Incidence of injuries in the 2006 New Zealand national junior rugby league competition. *New Zealand Journal of Sports Medicine, 34*(1), 21.

Knapik, J. J., Bauman, C. L., Jones, B. H., Harris, J. M., & Vaughan, L. (1991). Preseason strength and flexibility imbalances associated with athletic injuries in female collegiate athletes. *The American journal of sports medicine, 19*(1), 76-81.

Kobayashi, Y., Kubo, J., Matsubayashi, T., Matsuo, A., Kobayashi, K., & Ishii, N. (2013). Relationship between bilateral differences in single-leg jumps and asymmetry in isokinetic knee strength. *Journal of Applied Biomechanics, 29*(1), 61-67.

Kong, P. W., & Burns, S. F. (2010). Bilateral difference in hamstrings to quadriceps ratio in healthy males and females. *Physical Therapy in Sport, 11*(1), 12-17.

Kons, R. L., Diefenthaeler, F., Orssatto, L. B., Sakugawa, R. L., da Silva Junior, J. N., & Detanico, D. (2020). Relationship between lower limb asymmetry and judo-specific test performance. *Sport Sciences for Health, 16*, 305-312.

Kons, R. L., Orssatto, L. B. d. R., Sakugawa, R. L., da Silva Junior, J. N., Diefenthaeler, F., & Detanico, D. (2020). Effects of stretch-shortening cycle fatigue protocol on lower limb asymmetry and muscle soreness in judo athletes. *Sports Biomechanics, Publish ahead of print*.

Kozinc, Ž., Marković, G., Hadžić, V., & Šarabon, N. (2021). Relationship between force-velocity-power profiles and inter-limb asymmetries obtained during unilateral vertical jumping and singe-joint isokinetic tasks. *Journal of Sports Sciences, 39*(3), 248-258.

Kuenze, C., Pietrosimone, B., Lisee, C., Rutherford, M., Birchmeier, T., Lepley, A., & Hart, J. (2019). Demographic and surgical factors affect quadriceps strength after ACL reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy, 27*(3), 921-930.

Kyritsis, P., Bahr, R., Landreau, P., Miladi, R., & Witvrouw, E. (2016). Likelihood of ACL graft rupture: not meeting six clinical discharge criteria before return to sport is associated with a four times greater risk of rupture. *British Journal of Sports Medicine, 50*(15), 946-951.

Lai, W. C., Wang, D. A., Chen, J. B., Vail, J., Rugg, C. M., & Hame, S. L. (2017). Lower Quarter Y-Balance Test Scores and Lower Extremity Injury in NCAA Division I Athletes. *Orthopaedic Journal of Sports Medicine, 5*(8), Published online.

Lisman, P., Hildebrand, E., Nadelen, M., & Leppert, K. (2019). Association of Functional Movement Screen and Y-Balance Test Scores With Injury in High School Athletes. *Journal of Strength and Conditioning Research, 35*(7), 1930-1938.

Liu, T., & Jensen, J. L. (2012). Age-related differences in bilateral asymmetry in cycling performance. *Research Quarterly for Exercise and Sport, 83*(1), 114-119.

Loffing, F., Hagemann, N., Strauss, B., & MacMahon, C. (2016). *Laterality in sports: theories and applications*. London;Cambridge, MA;: Elsevier Academic Press.

Luedke, L. E., Geisthardt, T. W., & Rauh, M. J. (2020). Y-Balance Test Performance Does Not Determine Non-Contact Lower Quadrant Injury in Collegiate American Football Players. *Sports, 8*(3), 27.

Madruga-Parera, M., Romero-Rodríguez, D., Bishop, C., Beltran-Valls, M. R., Latinjak, A. T., Beato, M., & Fort-Vanmeerhaeghe, A. (2019). Effects of maturation on lower limb neuromuscular asymmetries in elite youth tennis players. *Sports, 7*(5), 106.

Mahajan, A. (2017). Use of star excursion balance test in assessing dynamic proprioception following anterior cruciate ligament injury. *International Journal of Orthopaedics, 3*(3), 01-05.

Mala, L., Maly, T., Cabell, L., Hank, M., Bujnovsky, D., & Zahalka, F. (2020). Anthropometric, body composition, and morphological lower limb asymmetries in elite soccer players: a prospective cohort study. *International Journal of Environmental Research and Public Health, 17*(4), 1140.

Malina, R. M. (2010). Early sport specialization: roots, effectiveness, risks. *Current Sports Medicine Reports, 9*(6), 364-371.

Malina, R. M., Cumming, S. P., Kontos, A. P., Eisenmann, J. C., Ribeiro, B., & Aroso, J. (2005). Maturity-associated variation in sport-specific skills of youth soccer players aged 13 – 15 years. *Journal of Sports Sciences, 23*(5), 515-522.

Maloney, S. J. (2019). The relationship between asymmetry and athletic performance: A critical review. *The Journal of Strength & Conditioning Research, 33*(9), 2579-2593.

Manoel, L. S., Xixirry, M. G., Soeira, T. P., Saad, M. C., & Riberto, M. (2020). Identification of Ankle Injury Risk Factors in Professional Soccer Players Through a Preseason Functional Assessment. *Orthopaedic Journal of Sports Medicine, 8*(6), Publish ahead of print.

Markovic, G., Šarabon, N., Pausic, J., & Hadžić, V. (2020). Adductor Muscles Strength and Strength Asymmetry as Risk Factors for Groin Injuries among Professional Soccer Players: A Prospective Study. *International Journal of Environmental Research and Public Health, 17*(14), 4946.

Marshall, B., Franklyn-Miller, A., Moran, K., King, E., Richter, C., Gore, S., . . . Falvey, É. (2015). Biomechanical symmetry in elite rugby union players during dynamic tasks: an investigation using discrete and continuous data analysis techniques. *BMC Sports Science, Medicine and Rehabilitation, 7*(1), 13.

McGrath, T. M., Waddington, G., Scarvell, J. M., Ball, N. B., Creer, R., Woods, K., & Smith, D. (2016). The effect of limb dominance on lower limb functional performance – a systematic review. *Journal of Sports Sciences, 34*(4), 289-302.

Mediouni, M. (2019). A new generation of orthopaedic surgeons: "T-model". *Current Orthopaedic Practice, 30*(5), 444-445.

Mediouni, M., R. Schlatterer, D., Madry, H., Cucchiarini, M., & Rai, B. (2018). A review of translational medicine. The future paradigm: how can we connect the orthopedic dots better? *Current Medical Research and Opinion, 34*(7), 1217-1229.

Michailidis, Y., Pirounakis, V., Savvakis, C., Margonis, K., & Metaxas, T. (2019). The influence of unilateral jumping asymmetry on acceleration and speed performance, in U10 and U15 groups of youth soccer players. *Trends in Sport Sciences, 26*(4).

Michailidis, Y., Savvakis, C., Pirounakis, V., Mikikis, D., Margonis, K., & Metaxas, T. (2020). Association between jump asymmetry and reduced performance in the change of direction tests of youth soccer players. *Journal of Physical Education and Sport, 20*(3), 1362-1368.

Michaud, P., Renaud, A., & Narring, F. (2001). Sports activities related to injuries? A survey among 9 – 19 year olds in Switzerland. *Injury Prevention, 7*(1), 41-45.

Micheli, L. J., & Klein, J. (1991). Sports injuries in children and adolescents. *British Journal of Sports Medicine, 25*(1), 6.

Miller, M. M., Trapp, J. L., Post, E. G., Trigsted, S. M., McGuine, T. A., Brooks, M. A., & Bell, D. R. (2017). The effects of specialization and sex on anterior Y-Balance performance in high school athletes. *Sports health, 9*(4), 375-382.

Mirwald, R. L., Baxter-Jones, A. D., Bailey, D. A., & Beunen, G. P. (2002). An assessment of maturity from anthropometric measurements. *Medicine and Science in Sports and Exercise, 34*(4), 689-694.

Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. (2010). Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *International Journal of Surgery (London, England), 8*(5), 336-341.

Nakagawa, T. H., dos Santos, A. F., Lessi, G. C., Petersen, R. S., & Silva, R. S. (2020). Y-Balance Test Asymmetry and Frontal Plane Knee Projection Angle During Single-leg squat as Predictors of Patellofemoral Pain in Male Military Recruits. *Physical Therapy in Sport, 44*, 121-127.

Neitzel, J. A., Kernozek, T. W., & Davies, G. J. (2002). Loading response following anterior cruciate ligament reconstruction during the parallel squat exercise. *Clinical Biomechanics, 17*(7), 551-554.

Newton, R. U., Gerber, A., Nimphius, S., Shim, J. K., Doan, B. K., Robertson, M., . . . Kraemer, W. J. (2006). Determination of functional strength imbalance of the lower extremities. *The Journal of Strength & Conditioning Research, 20*(4), 971-977.

Nyström, J., Lindwall, O., Ceci, R., Harmenberg, J., Swedenhag, J., & Ekblom, B. (1990). Physiological and morphological characteristics of world class fencers. *International Journal of Sports Medicine, 11*(2), 136-139.

Olmsted, L. C., Carcia, C. R., Hertel, J., & Shultz, S. J. (2002). Efficacy of the star excursion balance tests in detecting reach deficits in subjects with chronic ankle instability. *Journal of Athletic Training, 37*(4), 501-506.

Owens, E., Serrano, A., Ramsey, M. W., Mizuguchi, S., Johnston, B., & Stone, M. H. (2011). Comparing lower-limb asymmetries in NCAA DI male and female athletes. *The Journal of Strength & Conditioning Research, 25*, S44-S45.

Pappas, E., & Carpes, F. P. (2012). Lower extremity kinematic asymmetry in male and female athletes performing jump-landing tasks. *Journal of Science and Medicine in Sport, 15*(1), 87-92.

Pappas, P., Paradisis, G., & Vagenas, G. (2015). Leg and vertical stiffness (a) symmetry between dominant and non-dominant legs in young male runners. *Human Movement Science, 40*, 273-283.

Pardos-Mainer, E., Casajús, J. A., & Gonzalo-Skok, O. (2019). Adolescent female soccer players ' soccer-specific warm-up effects on performance and inter-limb asymmetries. *Biology of Sport, 36*(3), 199.

Patel, D. R., & Nelson, T. L. (2000). Sports injuries in adolescents. *Medical Clinics of North America, 84*(4), 983-1007.

Paterno, M. V., Schmitt, L. C., Ford, K. R., Rauh, M. J., Myer, G. D., Huang, B., & Hewett, T. E. (2010). Biomechanical Measures During Landing and Postural Stability Predict Second Anterior Cruciate Ligament Injury After Anterior Cruciate Ligament Reconstruction and Return to Sport. *American Journal of Sports Medicine, 38*(10), 1968-1978.

Pellicer-Chenoll, M., Serra-Añó, P., Cabeza-Ruiz, R., Pardo, A., Aranda, R., & González, L. (2017). Comparison of conventional hamstring/quadriceps ratio between genders in level-matched soccer players. *Revista Andaluza de Medicina del Deporte, 10*(1), 14-18.

Plisky, P. J., Gorman, P. P., Butler, R. J., Kiesel, K. B., Underwood, F. B., & Elkins, B. (2009). The reliability of an instrumented device for measuring components of the star excursion balance test. *North American Journal of Sports Physical Therapy, 4*(2), 92.

Plisky, P. J., Rauh, M. J., Kaminski, T. W., & Underwood, F. B. (2006). Star Excursion Balance Test as a predictor of lower extremity injury in high school basketball players. *Journal of Orthopaedic and Sports Physical Therapy, 36*(12), 911-919.

Pollock, K. M. (2010). *The star excursion balance test as a predictor of lower extremity injury in high school football players.* University of Toledo, Toledo.

Powell, J. W., & Barber-Foss, K. D. (1999). Injury patterns in selected high school sports: a review of the 1995-1997 seasons. *Journal of Athletic Training, 34*(3), 277-284.

Radelet, M. A., Lephart, S. M., Rubinstein, E. N., & Myers, J. B. (2002). Survey of the injury rate for children in community sports. *Pediatrics, 110*(3), e28.

Radzak, K. N., Putnam, A. M., Tamura, K., Hetzler, R. K., & Stickley, C. D. (2017). Asymmetry between lower limbs during rested and fatigued state running gait in healthy individuals. *Gait and Posture, 51*, 268-274.

Rahnama, N., Lees, A., & Bambaecichi, E. (2005). A comparison of muscle strength and flexibility between the preferred and non-preferred leg in English soccer players. *Ergonomics, 48*(11-14), 1568-1575.

Ramos, S., Simão, R., Herdy, C., Costa, P., & Dias, I. (2019). Relationship between strength and flexibility levels in young soccer players. *Apunts. Medicina de l'Esport, 54*(203), 85-90.

Rauh, M. J., Margherita, A. J., Rice, S. G., Koepsell, T. D., & Rivara, F. P. (2000). High school cross country running injuries: a longitudinal study. *Clinical Journal of Sport Medicine, 10*(2), 110-116.

Read, P. J., Oliver, J. L., Croix, M., Myer, G. D., & Lloyd, R. S. (2018). A prospective investigation to evaluate risk factors for lower extremity injury risk in male youth soccer players. *Scandinavian Journal of Medicine and Science in Sports, 28*(3), 1244-1251.

Read, P. J., Oliver, J. L., Croix, M. B. D. S., Myer, G. D., & Lloyd, R. S. (2016). Neuromuscular risk factors for knee and ankle ligament injuries in male youth soccer players. *Sports Medicine, 46*(8), 1059-1066.

Read, P. J., Oliver, J. L., Myer, G. D., Farooq, A., De Ste Croix, M., & Lloyd, R. S. (2020). Utility of the anterior reach Y-BALANCE test as an injury risk screening tool in elite male youth soccer players. *Physical Therapy in Sport, 45*, 103-110.

Rohman, E., Steubs, J. T., & Tompkins, M. (2015). Changes in involved and uninvolved limb function during rehabilitation after anterior cruciate ligament reconstruction: implications for limb symmetry index measures. *The American journal of sports medicine, 43*(6), 1391-1398.

Rössler, R., Junge, A., Chomiak, J., Němec, K., Dvorak, J., Lichtenstein, E., & Faude, O. (2018). Risk factors for football injuries in young players aged 7 to 12 years. *Scandinavian Journal of Medicine and Science in Sports, 28*(3), 1176-1182.

Ruffe, N. J., Sorce, S. R., Rosenthal, M. D., & Rauh, M. J. (2019). Lower quarter-and upper quarter Y balance tests as predictors of running-related injureis in high school cross-country runners. *International Journal of Sports Physical Therapy, 14*(5), 695-706.

Rutkowska-Kucharska, A. (2020). Asymmetry of lower limb strength and jumping ability of young soccer players. *Acta of bioengineering and biomechanics, 22*(1), 79-85.

Salem, G. J., Salinas, R., & Harding, F. V. (2003). Bilateral kinematic and kinetic analysis of the squat exercise after anterior cruciate ligament reconstruction. *Archives of Physical Medicine and Rehabilitation, 84*(8), 1211-1216.

Sannicandro, I., Cofano, G., Rosa, R. A., & Piccinno, A. (2014). Balance training exercises decrease lower-limb strength asymmetry in young tennis players. *Journal of Sports Science & Medicine, 13*(2), 397.

Sannicandro, I., Quarto, A., Piccinno, A., Cofano, G., & Rosa, R. A. (2014). Lower limb functional asymmetries in young soccer players: do differences exist between different age groups? *British Journal of Sports Medicine, 48*(7), 657-657.

Sant’Ana, J., Franchini, E., da Silva, V., & Diefenthaeler, F. (2017). Effect of fatigue on reaction time, response time, performance time, and kick impact in taekwondo roundhouse kick. *Sports Biomechanics, 16*(2), 201-209.

Sato, K., & Heise, G. D. (2012). Influence of weight distribution asymmetry on the biomechanics of a barbell back squat. *The Journal of Strength & Conditioning Research, 26*(2), 342-349.

Schiltz, M., Lehance, C., Maquet, D., Bury, T., Crielaard, J.-M., & Croisier, J.-L. (2009). Explosive strength imbalances in professional basketball players. *Journal of Athletic Training, 44*(1), 39-47.

Sieland, J., Krause, F., Kalo, K., Wilke, J., Vogt, L., Banzer, W., & Niederer, D. (2020). Injuries and functional performance status in young elite football players: a prospective 2-year monitoring. *Journal of Sports Medicine and Physical Fitness, 60*(10), 1363-1370.

Silva, R. S., Nakagawa, T. H., Ferreira, A. L. G., Garcia, L. C., Santos, J. E., & Serrão, F. V. (2016). Lower limb strength and flexibility in athletes with and without patellar tendinopathy. *Physical Therapy in Sport, 20*, 19-25.

Smith, C. A., Chimera, N. J., & Warren, M. (2015). Association of y balance test reach asymmetry and injury in division I athletes. *Medicine and Science in Sports and Exercise, 47*(1), 136-141.

Stege, J., Stubbe, J., Verhagen, E., & Van Mechelen, W. (2011). Risk factors for injuries in male professional soccer: a systematic review. *British Journal of Sports Medicine, 45*(4), 375-376.

Steidl-Muller, L., Hildebrandt, C., Muller, E., Fink, C., & Raschner, C. (2018). Limb symmetry index in competitive alpine ski racers: Reference values and injury risk identification according to age-related performance levels. *Journal of Sport and Health Science, 7*(4), 405-415.

Steinberg, N., Tenenbaum, S., Waddington, G., Adams, R., Zakin, G., Zeev, A., & Siev-Ner, I. (2020). Unilateral and bilateral patellofemoral pain in young female dancers: Associated factors. *Journal of Sports Sciences, 38*(7), 719-730.

Stephens, T. M., Lawson, B. R., DeVoe, D. E., & Reiser, R. F. (2007). Gender and bilateral differences in single-leg countermovement jump performance with comparison to a double-leg jump. *Journal of Applied Biomechanics, 23*(3), 190-202.

Stiffler, M. R., Bell, D. R., Sanfilippo, J. L., Hetzel, S. J., Pickett, K. A., & Heiderscheit, B. C. (2017). Star excursion balance test anterior asymmetry is associated with injury status in division I collegiate athletes. *Journal of Orthopaedic and Sports Physical Therapy, 47*(5), 339-346.

Sugiyama, T., Kameda, M., Kageyama, M., Kiba, K., Kanehisa, H., & Maeda, A. (2014). Asymmetry between the dominant and non-dominant legs in the kinematics of the lower extremities during a running single leg jump in collegiate basketball players. *Journal of Sports Science & Medicine, 13*(4), 951-957.

Taunton, J., Ryan, M., Clement, D., McKenzie, D., Lloyd-Smith, D., & Zumbo, B. (2003). A prospective study of running injuries: the Vancouver Sun Run “In Training” clinics. *British Journal of Sports Medicine, 37*(3), 239-244.

Tham, S. C., Tsou, I. Y., & Chee, T. S. (2008). Knee and ankle ligaments: magnetic resonance imaging findings of normal anatomy and at injury. *Annals-Academy of Medicine Sigapore, 37*(4), 324.

Thomas, R. E., Thomas, B. C., & Vaska, M. M. (2017). Injuries in taekwando: systematic review. *The Physician and sportsmedicine, 45*(4), 372-390.

Thompson, W. R., & Vinueza, C. (1991). Physiologic profile of tae kwon do black belts. *Research in Sports Medicine: An International Journal, 3*(1), 49-53.

Tomczak, M., & Tomczak, E. (2014). The need to report effect size estimates revisited. An overview of some recommended measures of effect size. *Trends in Sport Sciences, 21*(1), 19-25.

Trivers, R., Fink, B., Russell, M., McCarty, K., James, B., & Palestis, B. G. (2014). Lower body symmetry and running performance in elite Jamaican track and field athletes. *PloS One, 9*(11), e113106.

Tsolakis, C., & Tsiganos, G. (2008). The influence of training on neuromuscular factors in elite and non elite fencers. *Serbian Journal of Sports Sciences, 2*(1-4), 59-65.

Turner, A., Brazier, J., Bishop, C., Chavda, S., Cree, J., & Read, P. (2015). Data analysis for strength and conditioning coaches: Using excel to analyze reliability, differences, and relationships. *Strength & Conditioning Journal, 37*(1), 76-83.

Turner, A. N. (2009). Strength & conditioning for Taekwondo athletes. *Professional Strength & Conditioning*(15), 15-27.

Turner, A. N., Marshall, G., Phillips, J., Noto, A., Buttigieg, C., Chavda, S., . . . Kilduff, L. (2016). Physical characteristics underpinning repetitive lunging in fencing. *Journal of Strength and Conditioning Research, 30*(11), 3134-3139.

Ujaković, F., & Šarabon, N. (2020). Change of Direction Performance Is Influenced by Asymmetries in Jumping Ability and Hip and Trunk Strength in Elite Basketball Players. *Applied Sciences, 10*(19), 6984.

Vieira, L. H. P., de Souza Serenza, F., de Andrade, V. L., de Paula Oliveira, L., Mariano, F. P., Santana, J. E., & Santiago, P. R. P. (2016). Kicking performance and muscular strength parameters with dominant and nondominant lower limbs in Brazilian elite professional futsal players. *Journal of Applied Biomechanics, 32*(6), 578-585.

Warren, M., Lininger, M. R., Smith, C. A., Copp, A. J., & Chimera, N. J. (2020). Association of Functional Screening Tests and Noncontact Injuries in Division I Women Student-Athletes. *Journal of Strength and Conditioning Research, 34*(8), 2302-2311.

Webster, K. E., Austin, D. C., Feller, J. A., Clark, R. A., & McClelland, J. A. (2015). Symmetry of squatting and the effect of fatigue following anterior cruciate ligament reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy, 23*(11), 3208-3213.

Witvrouw, E., Danneels, L., Asselman, P., D'Have, T., & Cambier, D. (2003). Muscle flexibility as a risk factor for developing muscle injuries in male professional soccer players: a prospective study. *The American journal of sports medicine, 31*(1), 41-46.

Wong, P. L., Chamari, K., Chaouachi, A., Mao, D. W., Wisloff, U., & Hong, Y. (2007). Difference in plantar pressure between the preferred and non-preferred feet in four soccer-related movements. *British Journal of Sports Medicine, 41*(2), 84-92.

Yang, J., Tibbetts, A. S., Covassin, T., Cheng, G., Nayar, S., & Heiden, E. (2012). Epidemiology of overuse and acute injuries among competitive collegiate athletes. *Journal of Athletic Training, 47*(2), 198-204.

Zifchock, R. A., Davis, I., Higginson, J., McCaw, S., & Royer, T. (2008). Side-to-side differences in overuse running injury susceptibility: a retrospective study. *Human Movement Science, 27*(6), 888-902.

Appendix: Questionnaire for Training Information and Non-Contact Lower-Limb Injury in Pediatric-Age Athletes

This is a questionnaire designed for collecting information of your child's basic information, sport training, and non-contact lower-limb injury in the preceding 12 months.

1. Age: _______
2. Sex: _______
3. Sport specialized: _______
4. Dominant leg (the preferred leg for ball kicking): Right / Left
5. Length of training (years): _______
6. On average, how many times did your child participate in training each week?

1 ☐ 2 ☐ 3 ☐ 4 ☐ ≥ 5 ☐

7. On average, how vigorous was the training?

Mild ☐ Moderate ☐ Strenuous ☐

8. During the past 12 months, did your child have any non-contact lower-limb injury (occurred during training or competition) causing time loss for at least one day from participation in sport activities? Note: A day lost caused by injury is any day (including the day in which the participant was injured) where the participant was not permitted to or not able to participate in sporting activities in an unrestricted manner; lower-limb injuries that occurred at a time other than during training or competition, or were caused by contact with equipment or another player, should not be included.

   Yes No

9. If so, what did you injure?

Injury Position	
Hip	☐
Thigh	☐
Knee	☐
Shin	☐
Calf	☐
Ankle	☐
Foot	☐

10. What was the injury, to the best of your knowledge?

Dislocation	☐
Fracture (broken bone)	☐
Ligament Sprain	☐
Muscle Strain	☐
Shin Splints	☐
Sprain	☐
Stress Fracture	☐
Tendonitis	☐
Cramp	☐
Jumper's Knee	☐
Osgood-Schlatter	☐
Patellofemoral Pain	☐
Plantar Fasciitis	☐
Sever's Disease	☐
Turf Toe	☐
Other	☐