INTER-LIMB ASYMMETRIES AND SPORTS PERFORMANCE. FROM ASSESSMENT TO THE APPLICATION OF A SPORT-SPECIFIC ISO-INERTIAL RESISTANCE TRAINING IN YOUNG ATHLETES

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Inter-limb asymmetries and sports performance

From assessment to the application of sport-specific iso-inertial resistance training in young athletes

DOCTORAL THESIS

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2019

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List of publications

Regarding the studies presented in the publications section, those accepted in open access are shown in the original format, while those accepted in limited access are shown in the format of the accepted version (with the aim of respecting the editorial rights of the journals). Last, the articles under review are presented in a last version format as submitted to the journal.

Title of study 1 – *open access*

Effects of Maturation on Lower Limb Neuromuscular Asymmetries in Elite Youth Tennis Players

Citation:

Madruga-Parera, M.; Romero-Rodríguez, D.; Bishop, C.; Beltran-Valls, M.R.; Latinjak, A.T.; Beato, M.; Fort-Vanmeerhaeghe, A. Effects of Maturation on Lower Limb Neuromuscular Asymmetries in Elite Youth Tennis Players. *Sports* 2019, *7*, 106.

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Title of study 2

Jumping-based Asymmetries are Negatively Associated with Jump, Change of Direction, and Repeated Sprint Performance, but not Linear Speed, in Adolescent Handball Athletes

Citation:

Madruga-Parera M, Bishop C, Read P, Lake J, Brazier J, Daniel Romero-Rodríguez. Jumping-based Asymmetries are Negatively Associated with Jump, Change of Direction, and Repeated Sprint Performance, but not Linear Speed, in Adolescent Handball Athletes. *Journal of Human Kinetics.* 2020

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Title of the study 3

Interlimb Asymmetries in Youth Tennis Players: Relationships With Performance

Citation:

Madruga-Parera M, Bishop C, Fort-Vanmeerhaeghe A, Beltran-valls MR, Gonzalo-Skok O, Romero-Rodriguez D. Interlimb Asymmetries in Youth Tennis Players: Relationships With Performance. *J Strength Cond Res,* 2019 [Published ahead of print]

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Title of the study 4

Relationship Between Inter-limb Asymmetries and Speed and Change of Direction in Youth Handball Players

Citation:

Madruga-Parera M, Bishop C, Beato M, Fort-Vanmeerhaeghe A, Gonzalo-Skok O, Romero-Rodriguez D. Relationship Between Inter-limb Asymmetries and Speed and Change of Direction in Youth Handball Players. *J Strength Cond Res,* 2019 [Published ahead of print]

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Journal information:

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Title of study 5 *under review*

Effects of 8-weeks of Iso-inertial vs Cable-resistance Training on Motor Skill Performance and Inter-limb Asymmetries

Citation:

Madruga-Parera M, Bishop C, Beato M, Fort-Vanmeerhaeghe A, Gonzalo-Skok O, Romero-Rodriguez D. Effects of 8-weeks of Iso-inertial vs Cable-resistance Training on Motor Skill Performance and Inter-limb Asymmetries. *J Strength Cond Res,* 2019 [Published ahead of print]

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List of abbreviations

ACL: Anterior cruciate ligament injury

CMJ: Countermovement jump

COD: Change of direction

CODD: Change of direction deficit

CP: Conical pulley

D: Dominant leg

IN-COD: Iso-inertial change of direction

LE: Leg extension

LC: Leg-curl

ND: Non-dominant leg

RCOD: Repeated change of direction

PHV: Peak height velocity

SEBT: Star Excursion Balance Test

HT: Handball throwing test

UBJ: Unilateral broad jump

UDJ: Unilateral drop jump

UCMJ: Unilateral countermovement jump

ULJ: Unilateral lateral jump

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**Author's own figures, tables and photograph with the athlete's permission.*

Universitat de Girona

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I / WE DECLARE:

That the thesis entitled 'Inter-limb asymmetries and sports performance: From assessment to the application of sport-specific iso-inertial resistance training in young athletes', presented by Marc Madruga-Parera to obtain a doctoral degree, has been completed under my supervision and meets the requirements to opt for an International Doctorate.

In witness whereof, I hereby sign this document.

Signature

Girona, 1st September 2019

Azahara Fort-Vanmeerhaeghe, PhD, Faculty of Psychology, Education Sciences and Sport (FPCEE) and School of Health Sciences (FCS) Blanquerna, University of Ramon Llull, Barcelona, Spain.

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Signature

Girona, 1st September 2019

Al meu pare Antoni per acompanyar-me
des de la nostra platja
en aquest "camí net i clar".

A la meva mare Teresa i germanes, Laura i Maria,
perquè "malgrat la boira cal caminar",

A la meva neboda Isolda per ser
"la força que ens fa viure, viure i ser lliures"

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Some insights

"Every motor scheme will be reinforced by the variability of the practice"
N. Bernstein (1967)

"Qualsevol sistema viu, inclós el cos humà, és més que la suma de les seves parts"
E. Punset (2004)

"What really matters for success, character, happiness and vital achievements is a defined set of social skills, not just cognitive skills that are measured by conventional IQ tests"
D. Goleman (1995)

"If you're not prepared to be wrong, you'll never come up with anything original"
K. Robinson (2013)

"Posiblemente no nos confundimos al entender que los deportes de equipo son demasiado complejos para ser observados, comprendidos y enseñados desde la simplicidad conceptual que nos aporta el conocimiento de las teorías conductistas y mecanicistas, pues estas – con su visión lineal y monocausal – no abarcan la infinitud de alternativas de toda naturaleza que subyacen en el desarrollo del juego colectivo""
F. Seirul·lo (2017)

Contents

Before embarking on presenting this project, I would like to explain how I got to this point. I have always been involved in sport, mainly handball. At the hands of various professionals in this area, I was lucky enough to have the opportunity to train and live some incredible experiences in high-performance handball which, more importantly, taught me to be curious, demanding, and critical.

My interest in research started to emerge in 2012, when I was in my third year of a sports science degree, from the numerous conversations I had with my thesis supervisors Daniel Romero Rodriguez PhD, and Azahara Fort Vanmerhaeghe PhD, and my newly formed relationship with Alex Latinjak PhD, who had included me in a research group that had just been created in the university. It was then, and related to my end of degree project, that I began to focus on neuromuscular control and the analysis of neuromuscular risk factors in youth athletes.

Thanks to daily handball training sessions in a tennis school where I was in direct contact with athletes, and getting to know the professional researchers Julio Tous-Fajardo PhD, Oliver Gonzalo-Skok PhD, Victor Moreno-Pérez PhD, Javier Jorge-Vizuete PhD, and Chris Bishop, I was able to start out in the research area of inter-limb asymmetries and strength training with inertial resistance. This gave me the grounding to go on to observe how important strength training with a coordinative purpose is in the area of neuromuscular training, particularly in young athletes, during these four years of lectures, meetings, trips, and discussions.

My hope is that as the outcome of this personal process, the compendium of five papers. I have written for this doctoral thesis will not only increase knowledge about analysing and detecting inter-limb asymmetries and knowing their effect on performance in our profession, but will also add experience in researching the effects of iso-inertial resistances on assessment, improved performance, and the reduction of injury risk factors in multidirectional sports.

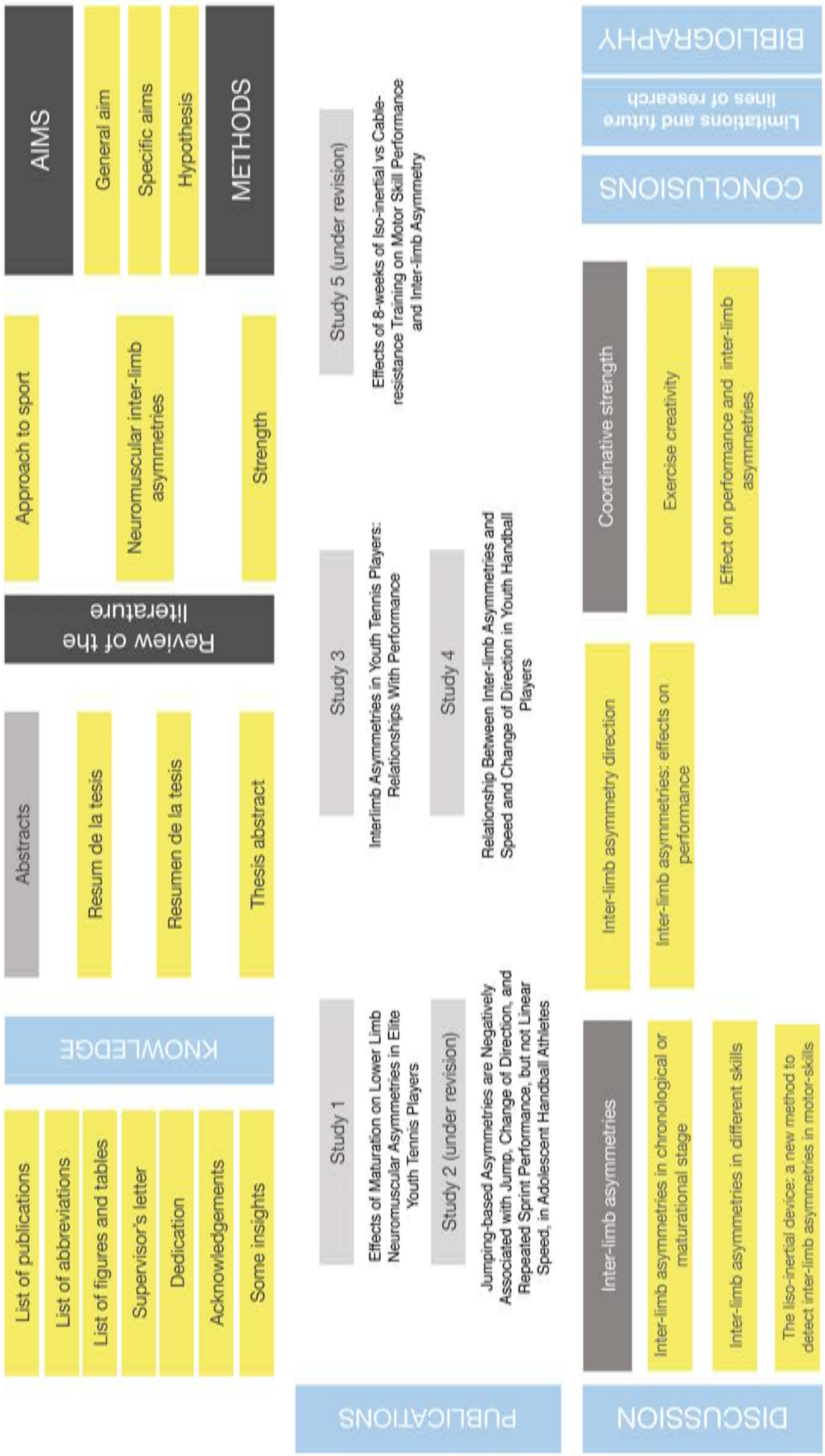

Figure 1. Outline of the doctoral thesis.
Map of the thesis, showing a graphical representation of the different sections that can be found in this document.

Abstract

Asimetries entre extremitats i rendiment esportiu

–De la valoració a la aplicació d'un entrenament específic amb resistència iso-inercial en joves esportistes–

L'handbol i el tennis són esports que utilitzen l'extremitat superior per llançar o colpejar una pilota, i on es desenvolupen desplaçaments multidireccionals que manifesten diferents habilitats específiques amb una màxima explosivitat. La literatura especialitzada defineix les asimetries entre extremitats inferiors com les diferencies de força o habilitat que es produeixen entre aquestes extremitats en el moment de realitzar una acció. Aquestes asimetries han estat estudiades, bàsicament, amb dues intencions: detectar possibles factors de risc de lesió, i estudiar si les mateixes afecten el rendiment de les habilitats de l'esportista, tals com el salt, el canvi de direcció (COD) i l'esprint. La literatura també ens mostra com el treball de força i potència muscular representa l'eina metodològica principal per a poder disminuir les asimetries i millorar el rendiment de l'esportista. Dins del treball d'aquesta capacitat, l'entrenament iso-inercial s'ha convertint, en els últims anys, en un instrument de treball que ja és considerat com un mètode contrastat en l'entrenament de força.

En base a aquests antecedents, aquesta tesi doctoral té com a objectiu quantificar i analitzar les asimetries en les habilitats de salt, COD, esprint i potencia muscular, així com comparar els efectes de l'entrenament amb resistència iso-inercial i resistència de cable gravitacional en joves esportistes. Per assolir aquests objectius, es van realitzar quatre estudis transversals (estudis 1, 2, 3 i 4) i un estudi longitudinal (estudi 5) en joves jugadors d'handbol i tennis, establint en cadascun d'ells l'edat madurativa dels subjectes. En el transcurs d'aquests estudis s'ha desenvolupat una bateria de valoracions de les habilitats esmentades. El COD ha estat testat en diferents condicions: a 90º i 180º, afegint una resistència inercial, i valorant la capacitat de repetir aquest tipus d'acció (resistència a la fatiga). Igualment, s'ha registrat la velocitat de l'esprint lineal, els salts en diferents direccions (vertical, horitzontal i lateral) i una acció de llançament específic de l'handbol. L'estudi 5 ha avaluat els efectes d'un programa d'entrenament de força de vuit setmanes de durada, on es comparaven els efectes de dues metodologies diferents, la iso-inercial i la gravitatòria per cable, sobre el rendiment de les habilitats motrius i la magnitud de les asimetries. Com a síntesi dels resultats d'aquest procés d'investigació, les asimetries detectades mostren variabilitat en les magnituds segons la prova seleccionada. En les valoracions de COD, s'han observat magnituds d'asimetria més elevades en el COD amb resistència iso-inercial (7.35% - 12.67%), COD dèficit (temps del COD – temps de l'esprint lineal) (5.48% - 10.52%) i capacitat de repetir COD (5.48%), en comparació als test més convencionals de COD de 90º i 180º (1.31% – 3.39%). Així mateix, el test de salt vertical va mostrar majors magnituds d'asimetria (8.76% – 17.55%) que els salts lateral (5.97% - 8.30%) i horitzontal (3.66% - 6.40%) en handbol i tennis. A més, s'ha pogut observar com els esportistes mostren preferències en l'habilitat de la cama en funció de la prova que es realitzi. Un aspecte que genera controvèrsia en la recent literatura, es centra en establir els efectes de les asimetries en el rendiment. Els nostres resultats mostren que les asimetries influeixen moderadament en el rendiment del COD, la capacitat de repetir COD, la velocitat en l'esprint lineal i el salt.

Per a finalitzar, hem pogut observar que un entrenament de força amb accions coordinatives i proper a l'especificitat esportiva té efectes positius en la millora del rendiment en joves jugadors d'handbol. A més, l'entrenament amb resistència iso-inercial mostra majors efectes en el rendiment en el COD multidireccional, la capacitat de repetir COD, el salt i el llançament, així com majors reduccions d'asimetries en el salt vertical, en comparació a l'entrenament de força convencional de cable gravitacional. També és important destacar que les adaptacions positives provocades per un entrenament de força no necessàriament s'associen a una reducció d'asimetries.

Paraules clau

Asimetries; handbol; tenis; entrenament iso-inercial; canvi de direcció.

Asimetrías entre extremidades y rendimento deportivo

–De la valoración a la aplicación de un entrenamiento específico con resistencia iso-inercial en jóvenes deportistas–

El balonmano y el tenis son deportes que utilizan la extremidad superior para lanzar y golpear una pelota, y en donde se desarrollan desplazamientos multidireccionales que manifiestan diferentes habilidades específicas con una explosividad máxima. La literatura especializada define las asimetrías entre extremidades inferiores como las diferencias de fuerza o habilidad que se producen entre estas extremidades en el momento de realizar una acción. Estas asimetrías han estado estudiadas, básicamente, con dos intenciones: detectar posibles factores de riesgo de lesión, y estudiar si las mismas afectan al rendimiento de las habilidades del deportista, tales como el salto, el cambio de dirección (COD) y el esprint. La literatura también nos muestra cómo el trabajo de fuerza y potencia muscular representa la herramienta metodológica principal para poder reducir las asimetrías y mejorar el rendimiento del deportista. Dentro del trabajo de esta capacidad, el entrenamiento iso-inercial se ha convertido, en los últimos años, en un instrumento de trabajo que ya es considerado como un método contrastado en el entrenamiento de fuerza.

En base a estos antecedentes, esta tesis doctoral tiene como objetivo cuantificar y analizar las asimetrías entre extremidades en las habilidades de salto, COD, esprint y potencia muscular, así como comparar los efectos del entrenamiento con resistencia iso-inercial y resistencia de cable gravitacional en jóvenes deportistas. Para lograr estos objetivos, se realizaron cuatro estudios transversales (estudios 1, 2, 3 y 4) y un estudio longitudinal (estudio 5) en jóvenes jugadores de balonmano y tenis, estableciendo en cada estudio la edad madurativa de los sujetos. En el transcurso de estos estudios se ha desarrollado una batería de valoraciones de las habilidades mencionadas. El COD ha sido evaluado en distintas condiciones: a 90º y 180º, añadiendo una resistencia iso-inercial, y valorando la capacidad de repetir este tipo de acción (resistencia a la fatiga). Igualmente, se ha registrado la velocidad del esprint lineal, los saltos en distintas direcciones (vertical, horizontal y lateral) y una acción de lanzamiento específico de balonmano. El estudio 5 ha evaluado los efectos de un programa de entrenamiento de fuerza de ocho semanas de duración, donde se comparaban los efectos de dos metodologías distintas, la iso-inercial y la gravitatoria por cable, sobre el rendimiento de las habilidades motrices y de la magnitud de las asimetrías.

Como síntesis de los resultados de este proceso de investigación, las asimetrías detectadas muestran variabilidad en las magnitudes según la prueba seleccionada. En las valoraciones de COD se han observado magnitudes de asimetría más altas en COD con resistencia iso-inercial (7.35% - 12.67%), COD dèficit (tiempo del COD –

tiempo del esprint lineal) (5.48% - 10.52%) y la capacidad de repetir COD (5.48%), en comparación a tests más convencionales de COD de 90º i 180º (1.31% – 3.39%). Asimismo, el test de salto vertical mostró mayores magnitudes de asimetría (8.76% – 17.55%) que el lateral (5.97% - 8.30%) y horizontal (3.66% - 6.40%) en balonmano y tenis. Además, se ha podido observar cómo los deportistas muestran preferencias en la habilidad de la pierna en función de la prueba que se realice. Un aspecto que genera controversia en la reciente literatura, se centra en establecer los efectos de las asimetrías entre extremidades y el rendimiento. Nuestros resultados muestran que las asimetrías influyen moderadamente en el rendimiento en el COD, la capacidad de repetir COD, la velocidad en esprint lineal y el salto.
Para finalizar, hemos podido observar que un entrenamiento de fuerza con acciones coordinativas y próximas a la especificidad deportiva tiene efectos positivos en la mejora del rendimiento en jóvenes jugadores de balonmano. Además, el entrenamiento con resistencia iso-inercial muestra mayores efectos en el rendimiento en el COD, el salto y el lanzamiento, así como mayores reducciones de asimetrías en el salto vertical que el entrenamiento de fuerza convencional de cable gravitacional. También es importante destacar que las adaptaciones positives provocadas por un entrenamiento de fuerza no necesariamente se asocian a una reducción de asimetrías.

Palabras clave:
Asimetrías; balonmano; tenis; entrenamiento iso-inercial; cambio de dirección.

Inter-limb asymmetries and sport performance

–From assessment to the application of sport-specific iso-inertial resistance training in young athletes–

Handball and tennis are sports in which the upper limbs are used to throw or hit a ball, and where multi-directional movements, involving different specific skills with maximum explosivity, are developed. The literature defines lower-limb asymmetries as the differences in strength or skill which are produced when an action is performed. These asymmetries have been studied with two main intentions: to detect possible injury risk factors, and to evaluate whether they affect athletes' performance when jumping, changing direction and sprinting. The literature also demonstrates how work on muscular strength and power is the main methodological tool to reduce asymmetries and improve athletic performance. In recent years, iso-inertial training has become known as an alternative to strength training.

This thesis aims to quantify and analyse inter-limb asymmetries in jumps, changes of direction (COD), sprints and muscular power, while comparing the effects of iso-inertial and cable-resistance training in young athletes. In order to achieve these objectives, five studies (four transversal and one longitudinal) of young handball and tennis players, whose maturational age had been established, were carried out. A functional test battery of the aforementioned skills was developed throughout the studies. COD was tested in different conditions: at 90° and 180°, adding an iso-inertial resistance, and evaluating the capacity to repeat this type of action (resistance to fatigue). The results of linear sprints, vertical, horizontal and lateral jumps, and a specific handball throwing action were also recorded. Study 5 evaluated the effects of an eight-week strength-training programme on performance of motor skills and magnitudes of inter-limb asymmetry. Two methodologies were compared: iso-inertial and cable-resistance.

The results of this research show that the magnitude of observed inter-limb asymmetries varies according to the test.

In COD assessments, greater magnitudes of inter-limb asymmetry have been observed in COD with iso-inertial resistance (7,35% - 12,67%), COD deficit (COD time – linear sprint time) (5.48% - 10.52%) and capacity to repeat COD (5.48%) than in COD 90º and 180º (1.31% – 3.39%). Likewise, the vertical jump test demonstrated larger magnitudes of inter-limb asymmetry (8,76% - 17,55%) than in lateral (5.97% - 8.30%) and horizontal (3.66% - 6.40%) in handball and tennis. Furthermore, we noted that athletes demonstrate different lower-limb preferences depending on the test. One aspect which has generated controversy in recent literature focuses on the effects of inter-limb asymmetries on performance. Our results show that inter-limb asymmetries have a moderate influence on COD, the capacity to repeat COD, linear sprint and jump performance.

To conclude, we have observed that strength training with sport-specific COD actions have a positive impact on the performance of young handball players. Furthermore, iso-inertial resistance training demonstrates improved performance in multi-directional COD, the capacity to repeat COD, jumps and throwing; along with greater asymmetry reduction in vertical jumps than with cable-resistance training. It is also important to underline the fact that positive changes caused by strength training do not necessarily mean a reduction in inter-limb asymmetries.

Key words

Asymmetries; handball; tennis; iso-inertial training; change of direction.

Review of the literature

Approach to sport

Sport among the youth population

Taking part in sporting activity during the different developmental stages has increased in popularity considerably in recent years (1), with the resulting benefits at the affective, physical, and psychological levels (2). However, increased competitiveness and more pressure on results and competing has resulted in a higher frequency and level of the training demanded of young people who are insufficiently psychologically mature (3). All this is evidenced by a growing trend in early specialisation programmes in which it is difficult to effectively assimilate training loads (4,5). Bompa and Haff (6) evidence the rapid results produced by this type of programme, but also point out the following negative effects: inconsistency in competition performances, increased injury risk, higher drop-out rate from the sport, and negative effects on the maturation process. Moreover, other authors have suggested that doing just one sport is not advantageous for becoming a professional sportsperson (4,5,7,8), and that multisport involvement has more positive effects at the coordination level than doing just one sport (9).

In this line, several studies examine the positive effects of long-term training methods (6,10,11) characterised by programming each of the conditional abilities depending on the young person's maturation process in order to improve acquisition of and adaptation to each of them. Lloyd and Oliver (12) carried out a study in the prepubescence stage, focusing on strength, fundamental skills, speed, and agility, and incorporating sport-specific skills, power, and hypertrophy in the adolescent stage. In the same line, in a two-year study of young footballers (U17-U18-U19) Sander et al. (13) observed that a training programme based on strength with a long-term objective resulted in a 6% improvement in sprinting compared with the group who only performed routine soccer training.
Considering these studies, it seems appropriate to include fundamental motor skills in sport training, both for the benefits in movement variability and quality and for the positive organic adaptations related to health (14). Figure 2 shows an example of the development of fundamental motor skills in young handball players.

Figure 2. Fundamental Motor skills in kids.
This exercise is developing neuromuscular ability, basic motor skills, and creativity in young handball players. Creativity in designing the tasks and the use of different materials heightens young athletes' motivation.

These training drills (strength, fundamental skills, speed, and agility, and incorporating sport-specific skills, power, and hypertrophy) implemented throughout the different developmental stages are important, since changes brought about by maturation can greatly influence both training processes and possible injury risk factors (8,15,16). In a study involving young footballers, Malina et al. (17) observe how degree of maturity (weight and height) can influence performance in the vertical jump and speed in the 30m sprint. In this line, different authors defend the need to analyse and compare training processes using the variables chronological age and biological age (18,19). In their review, Radnor et al. (20) state that as the child matures during growth, their ability to jump naturally improves due to aspects to do with structure and nerves, among other factors such as adaptation in the muscle and tendon tissue (their increased rigidity) and a greater capacity to recruit and preactivate motor units (positive effects on the stretch-shorten cycle and force production). While a direct association between the changes that occur in the sensorimotor system during adolescence and a greater or lower risk of suffering injury cannot be made (21), it has been determined that peak height velocity (PHV) is the stage when the most neuromuscular control changes occur in the lower limbs (22,23). Considering this circumstance, the estimation of maturational stages is a key point in the design of training programs and the detection of risk factors of injury, with the intention to create the right environment leading to beneficial adaptations in the youth population.

Neuromuscular training

Deficits in neuromuscular are associated with negative effects on sport performance, influencing the skills of jumping (24) and jump landing (21), and the change of direction (25). For this reason, neuromuscular training in youth has become a major point of interest and is one of the focuses of study aimed at improving performance and preventing injuries (26). Neuromuscular training has been introduced into the sports context, mainly during warm up, with the aim of improving performance (27) and preventing injuries (26). For example, Herman et al. (28) present the content to be included in a neuromuscular warm up, which should feature stretching, strength, and balance work, in addition to jump landing techniques and sport-specific skills work.

Figure 3. Integrative neuromuscular training in tennis
Example of integrative neuromuscular training in a young tennis player involving the action of balance when hitting the ball. In this task, apart from developing different changes of direction, the player must ensure precise activation of the leg and hip stabilising muscles and good trunk stabilisation when hitting the ball. The perceptive stimulus accentuates the external focus of attention and is highly specific given that it simulates a specific situation in the game.

The subject of neuromuscular training has also been addressed from the perspective of its application during the training process, using an integrated methodology and with a content that includes the basic skills of the sport and specific strength and conditioning work (26). Sport science professionals must view this proposal as a challenge to devise tasks with added creativity, with the aim of simulating complex situations in training that allow the athlete to experience and take part in the learning process, and fostering greater adaptation and motivation in the process (Figure 3).

Sport abilities

Multidirectional situational sports, with or without a shared space (such as handball and tennis, respectively), are characterised by the intermittent movements occurring in multiple directions and in direct response to the action of the opponents. Although the physiological parameter tends to carry most weight when classifying sports, here we use sport skills as the preferred criteria for comparing sports of this type. In these sports, the different forms of change of direction (COD) and jumps are especially important.

Change of direction in multidirectional sports: handball and tennis

One of the most frequently occurring skills in most of these sports is the change of direction. Handball is characterized by intermittent efforts in which actions requiring maximal effect occur every 3.2 seconds, and approximately 1459m is covered in a match (29). Notably, some 66 m of this distance is covered by means of lateral movements, according to data recorded by Michalsik et al. (29), and there are multiple acceleration, deceleration, and changes of direction actions (30,31). The change of direction is recognised as one of the decisive skills in the different phases of play in handball (29), both in the offensive (possibility, for example, to overtake the adversary and develop manoeuvres in combination with team members) and defensive actions (possibility to be more reactive, for example being able to act upon a direct opponent or help defend with moves of varying distance depending on the defensive system and the specific position). The differences between the two phases lie in how the players are positioned on the court, which can determine the speed of the actions and their preferred side and angle. Another characteristic of handball is that most of

these actions are carried out with the ball which, due to the attentional focus, can become a determinant in the sport's change of direction actions (32).
In the case of tennis, the displacements made by players average 4m (33) of which 70% are lateral movements (34,35). The average number of changes of direction per point is four (36), with the distinctive features that the displacements are made with a racket and, depending on the hitting technique employed, the number of supports on each side can vary.

Figure 4. Specific hitting situation in tennis.
Example of a specific displacement and hitting move in tennis, increasing our understanding of the movements made in the specific context of the sport.

It is important to remember that the change of direction is a complex action, which calls for different braking strategies depending on the number of paces taken (37–39), optimum trunk stability (39), appropriate eccentric muscular action prior to the eccentric-concentric action in order to accelerate immediately as required (40,41), and an the capacity to change direction at multiple angles (38,42). Special attention must be paid to the number of changes of direction made in a state of fatigue during a match, which may not only make the ability to repeat changes of direction a determinant in performance (43), but also means this should be considered as an injury risk factor, especially for anterior cruciate ligament injury (ACL) (44,45). Given the weight of this motor skill in handball and tennis, the need to evaluate COD actions in an isolated way becomes of great interest, as well as the need to develop training programs centered, especially, in the development of this skill.

Jumping in multidirectional sports: handball and tennis

In handball, a player jumps approximately 90 times per match (46). This skill is executed as most often using both legs, mainly in defensive blocking actions. The 75% of the throwing actions are carried out with jumps executed unilaterally, normally using the limb on the opposite side to the one being used to throw (i.e. left leg jump out for a right handed throw) (47). In tennis, on the other hand, the jump is used mainly during the serve, given that the aim is to transfer the force generated in the lower limb to the arm used to execute the serving action (48).

Because of the great meaning of this ability in different sports, the relationship between jumping capacity and sport performance has become a field of interest. Loturco et al. (49) compared the effects of a training program including squats or countermovement jumping actions, and both methodologies led to better performance in vertical jump. These authors evidenced a relationship between vertical forces and jumping performance, and other investigations (49–52) have also shown an association among vertical forces, acceleration and lineal sprint performance. Related to these studies, Loturco et al. (52), more recently, have identified jumping training with slight load and moderate intensity to improve sport performance in multidirectional specialities.

Assessments

In this section, we address an aspect that is becoming increasingly decisive in the practice of training: athlete assessment, the purpose of which is to analyse performance and possible injury risk factors. Assessments must fulfill the conditions of reliability (testing what you are supposed to be testing), reproducibility (how reproducible the measure is), sensibility (ability to detect changes over the time), and specificity (the need to know if it approximates the requirements of the sport or not) (53). As shown in Figure 5, the data obtained from an assessment can have multiple uses: to carry out research, to analyze injury risk factors, to construct a profile of the different team variables, to observe the effects of a specific intervention, to follow up on a training process, or to construct an athlete's individual profile. The possible objectives of these actions are to improve sports performance, monitor the state of the athlete, prescribe training schedules, prevent injuries, detect risk factors, and decide on each phase of post-injury return to play processes.

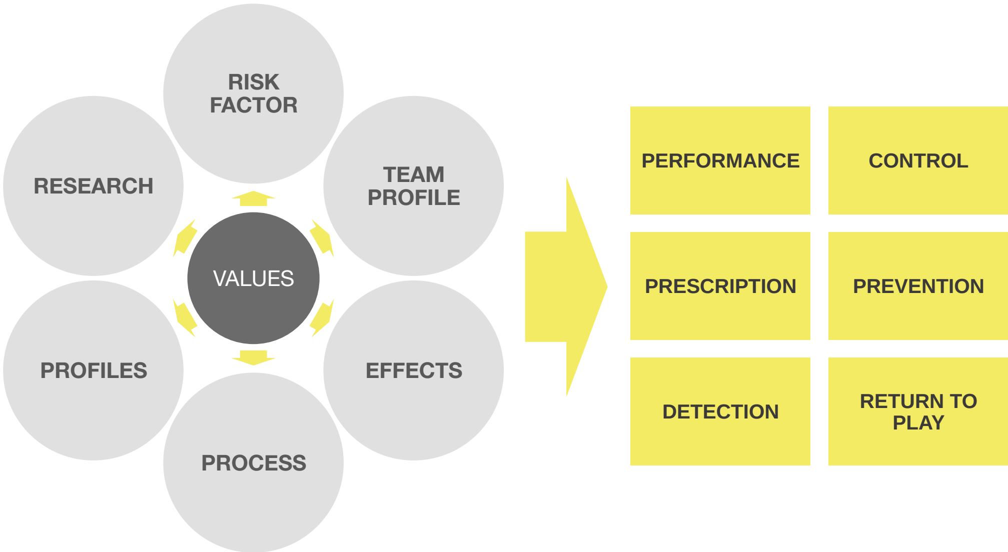

Figure 5. Application of the data obtained in the assessments

Due to the myriad aims and objectives of assessment, establishing selection criteria for each test is a challenge. In a recent study, Loturco et al. (54) found no relationship between different tests (tensiomyography, jumps, and isokinetic tests) administered to young footballers. In the same line, Bishop et al. (55) observed different behaviour in the nature of inter-limb asymmetries (a subject discussed in greater depth later) depending on the jump tests selected. These studies suggest the need to determine basic criteria when choosing which test to administer in each situation. Another related aspect to consider is devising tests that reproduce kinematic patterns typical of competitions, with the added possibility of introducing specific perceptive and decision-making components, as suggested by Young and Farrow (56) in relation to designing agility training. Emerging from this perspective and from reflections made on the matter, a proposal related to the levels of functionality and specificity of each test has recently been made (Figure 6) (57).

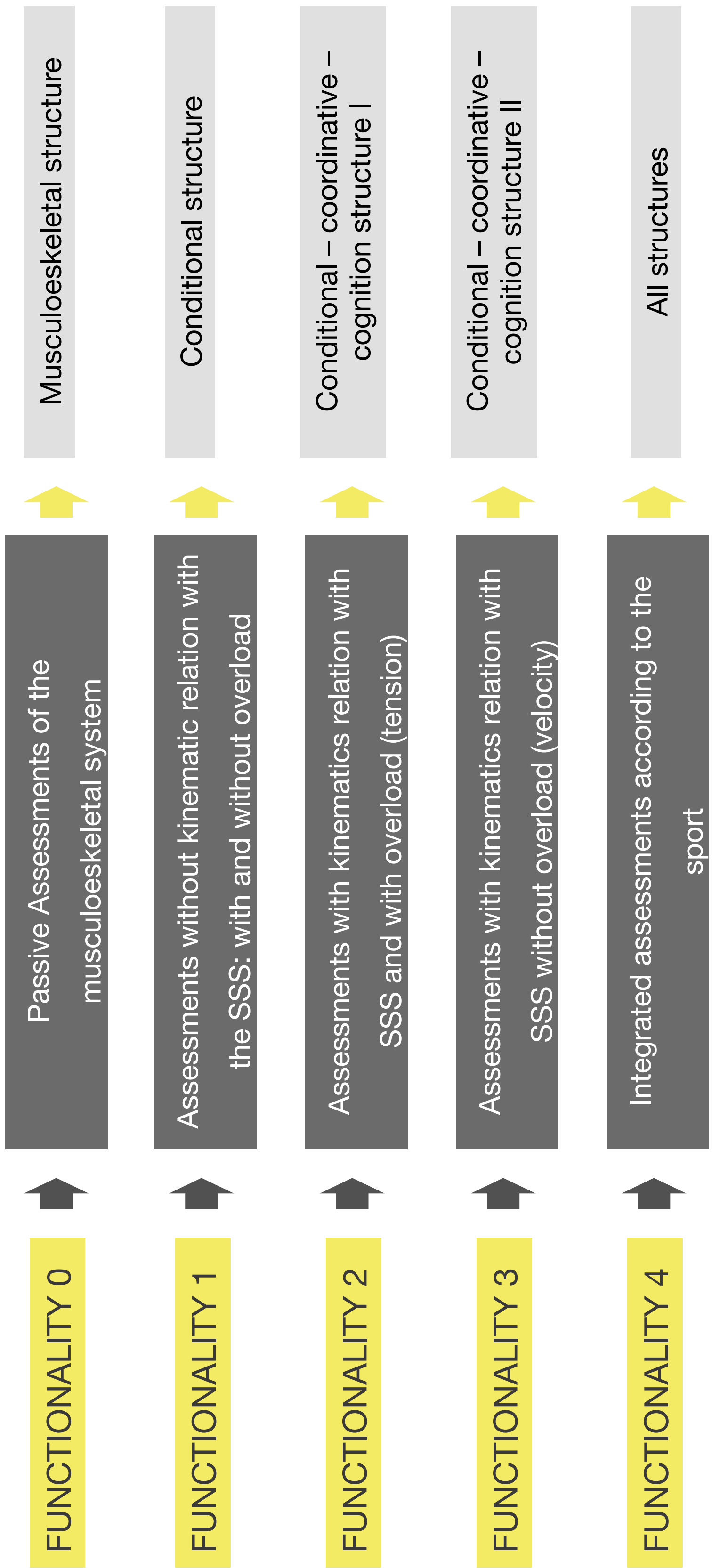

Figure 6. Levels of functionality of the assessments.
This diagram shows the levels of functionality of the assessments established by Romero-Rodríguez and Madruga-Parera (57), in which the five levels are expressed in relation to proximity to the characteristics of the sport.

As shown in Figure 6, the different types of tests can be classified as follows:

- Level 0: Passive assessments of the musculoskeletal system, with no relation to the characteristics of the sport, and with no active intervention of any type such as, for example, tensiomyography and ecography.
- Level 1: Active assessments with no kinematic relation to sport-specific skills, with and without overload; this group would include some actions already commonly tested in different tests such as analytical movements like leg extensions and leg curls, more complex actions such as the squat, and assessments of balance such as the Star Excursion Balance Test (SEBT), among others.
- Level 2: Assessments with kinematic relation to sport-specific skills and with overload, introducing conditional, coordinative, and possibly cognitive elements; here we can include different jump, change of direction, and sprint tests, among other possibilities.
- Level 3: Assessments with kinematic relation to the sport and without overload, bringing the test closer to the specific characteristics of the sport, with conditional, coordinative, and possibly cognitive implications (speed in the change of direction, and specific jumps and throws, to cite some examples).
- Level 4: Integrated assessments depending on the sport. In this as yet unexplored level of functionality we can place the analysis of performance scores with GPS, and evaluating parameters such as sprints and accelerations and decelerations, among other possibilities, in tests that can simulate competition.

This classification is made with the intention to provide a better understanding of the different tests created to evaluate motor skills as balance, multidirectional jumps, change of direction and repeated change of direction actions. All these assessments can be adapted to be applied in different settings.

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Neuromuscular inter-limb asymmetries

Approach

Inter-limb asymmetries refers to the difference in function or performance between limbs (58,59). Different authors have examined asymmetries for varying purposes and from different perspectives. From the neuromuscular point of view, this topic has been associated with the objective of controlling injury risk factors, thus intervening in the field of injury prevention (26,60). A second perspective is focused on controlling asymmetries to monitor an athlete's progress during the post-injury back to play phase (60), in other words, controlling existing differences between limbs (injured/non-injured) during a recovery process, such as may be necessary after ACL reconstruction, one of the most studied injury processes (61–66). Last, and as mentioned in previous sections, administering tests that detect asymmetries has also been used as a way of studying their possible influence on athletic performance (67–70).

Inter-limb asymmetries have been tested in several different sports such as basketball (71–74), volleyball (75), American football (76), rhythmic gymnastics (77), tennis (78), and football (79). However, the real influence of asymmetry on sports performance and injury risk is not completely known. Therefore, this issue still deserves further studies to better elucidate if asymmetric athletes are more prone to developing injuries or to demonstrating decreased performance levels. Finally, it is not only important to detect asymmetric athletes, but also the methods to detect asymmetry deserve more investigations.

Detection of inter-limb asymmetries

Determining which is the dominant leg to be able to quantify asymmetries between the lower limbs is a subject of debate in this area of research. The terms 'dominant leg' and 'non-dominant leg' have been used and these have been identified through various means, for example, the limb used for kicking a ball (80), going up a step (81), and gaining one's balance after being pushed unexpectedly (82). However, there are other criteria to determine asymmetries such as the 'strong leg' and the 'weak leg' when carrying out a task (58), the strong leg and the weak leg in relation to a skill (74) and, more recently, the dominant leg and the non-dominant leg in relation to varying performance in the tests administered (53,83). This last has been related to tests that provide data about the skills of balance, jumping, and change of direction, making determining the dominant lower limb dependent, to a large degree, on the skill being assessed (84). This way of understanding dominance makes sense if we take into account, for example, that the non-preferred leg when kicking, which will be the one the player uses as a support when carrying out this action (85), will very likely be the dominant leg in a vertical jump or the one used for a one-leg balance to assess balance. A coherent methodology must therefore be established not only to determine and analyse the dominant leg, but also to be taken into consideration in relation to directionality and the size of asymmetries, parameters that will be discussed in later sections.

As is generally the case with sports assessment, wide range of methodologies have been put forward to detect asymmetries. For example, there are muscular strength assessments using isokinetic machines that bear no relation to actual sporting situations and are used, for example, after finishing a training programme (86,87) and also in clinical situations, such as the case study of the ACL injury (88). However, such assessments may carry little correspondence to typical athletic movements. Moreover, the required equipment, technical expertise and time for measurement-analysis may contraindicate such assessment in many instances. Conversely, when increasing the functionality of the assessment, it is normal to develop the work of different skills and physical qualities jointly, but usually within the use of non-specific sport force vectors direction. This is the case of working, for example, bilateral squats and unilateral jumping actions, skills that can be carried out under the control of force platforms to study the dynamics of the forces generated (53,65), and using video cameras that enable the movement to be analysed cinematically (89–91). More closely related to sport, multidirectional jumps (92–94) and change of direction actions are also assessed, which can have a more functional objective (95). Among the different types of change of direction tests (80,96,97) and the study of the so-called change of direction deficit (CODD), defined as a measure of how much of one's maximal sprint velocity could be used or maintained despite the changes of direction required during a given COD task (98,99). Nonetheless, approaches to assessing asymmetries should consider to the specific needs of the sport, as it has shown in the classification proposed by Romero-Rodríguez and Madruga-Parera (57). Given this situation, and in line with this classification, a non-published study was carried out and presented at the international JAM Sports conference, which evidences the different magnitudes of lower limb asymmetries in tests of varying levels of specificity (1, 2, and 3) (100) (Figure 7).

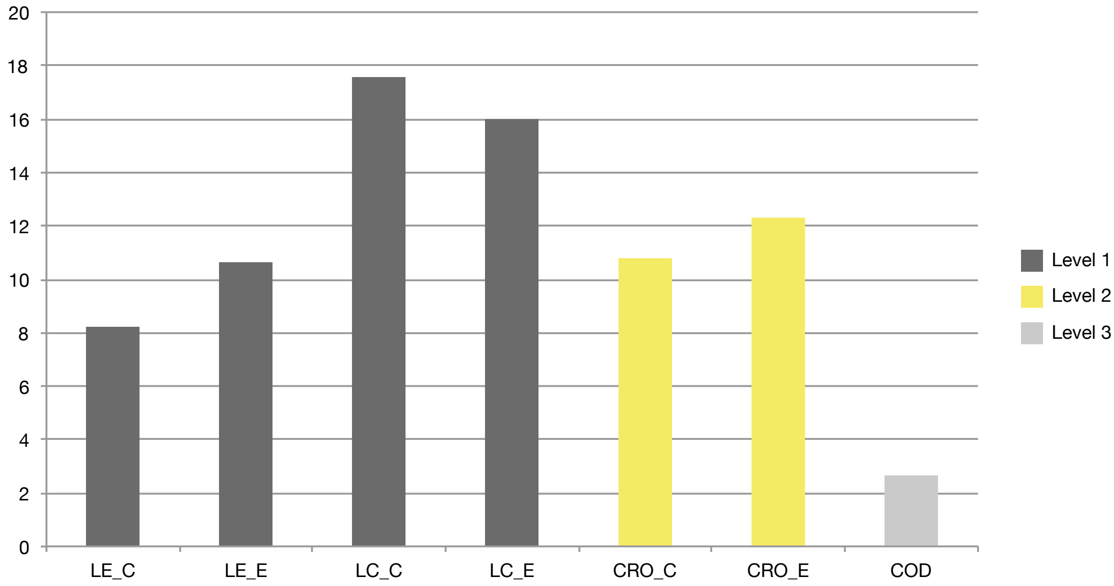


Figure 7. Inter-limb asymmetries according to the levels of functionality proposed by Romero-Rodríguez and Madruga-Parera (57). Level 1: Leg-extension (LE) and Leg-curl (LC) with eccentric overload; Level 2: Crossover step (CRO) with eccentric overload; Level 3: speed in the change of direction (COD) in soccer players. C: Concentric; E: Eccentric.

Although the findings are explored in greater depth in the discussion section of this thesis, some points derived from this study are worth mentioning here: the asymmetries in level 1 open-chain isolated assessments (especially in the leg-curl test (LC)) reveal asymmetries of a greater magnitudes than those found in the more functional tasks (level 3, change of direction speed (COD)); the more specific COD action presents the lowest asymmetries; and carrying out the isolated and resisted change of direction (level 2) by means of an inertial device gives an asymmetry that tends to be between three and four times higher than the most functional COD one. According to this reasoning, it is interesting to detect neuromuscular asymmetries depending on the level of specificity, with the intention to know if the magnitude of this parameter fluctuates with specificity. Similarly, it is also of interest to study asymmetry values depending on the kind of muscular action, i.e. the differences of asymmetry during the eccentric and concentric actions in a stretch-shortening cycle.

Analysis of inter-limb asymmetries

Related to the previous point, centered on the kind of tests carried out to detect asymmetries, the present one, focused on the type of analysis used to quantify them, is of relevant significance. There are many existing formulas for establishing the asymmetries index, which is the main reason why Bishop et al. (101) recently compiled a review that aimed to make the investigation and detection of asymmetries and the asymmetry indexes obtained more consistent. Their manuscript presents the different formulas used and show how varied the indexes can be depending on the criteria and formulas chosen. The importance of separating the analyses carried out into tests of unilateral actions must be underlined with the following formula recommended for calculating unilateral asymmetries [100/(max value)*(min value)*-1+100] (102). Finally, with regards to the validity of the data obtained, it is agreed that inter-limb asymmetry values will be acceptable when they will be greater than the coefficient of variation (84). This is an important matter in inter-limb asymmetry analysis to ensure that the information obtained is conclusive.

Magnitude of inter-limb asymmetries

As previously mentioned, the different tests used to detect asymmetries may reveal very different magnitudes, particularly depending on the functionality of the tests. One of the most used assessments is the vertical jump, with the countermovement jump (69) and drop jump (67) showing the most asymmetry. Despite it not being the most specific jump at the level of the kinematics of sport, the vertical countermovement jump is the most used test due to its reproducibility, reliability, and ease of administration (53). Table 1 shows the different asymmetry magnitudes according to the sport and the type of jump, and includes backward and lateral jumps, the drop jump, and the triple hop.

Table 1. Jumping inter-limb asymmetries magnitude						
Author	Sport	CMJ (%)	LJ (%)	BJ (%)	DJ (%)	TH (%)
Hewit et al.(82)	Female Netball U21	7.8	6.2	4.6	-	-
Lockie et al.(93)	Male Recreational team sports Age: 22.6	10.4	3.3	5.1	-	-
Sannicandro et al.(78)	Male-female Tennis Age: 13.0	-	10.8*	9.0*	-	-
Fort-Vanmeerhaeghe et al.(74)	Female Basketball Age:15.6	14.1	3.3	3.8	-	-
Fort-Vanmeerhaeghe et al.(75)	Male-female volleyball - basketball Age: 24.0	12.3	-	-	-	-
Bishop et al.(103)	Female Soccer U17	11.5	-	-	7.9	-
Bishop et al.(70)	Male Soccer U23-18-16	U23: 6.0 U18: 7.5 U16: 9.0	-	-	-	-
Bishop et al.(67)	Female Soccer Age: 20.5	8.6	-	-	9.2	-
Bishop et al.(69)	Female Soccer Age: 10.0	12.5	-	6.8	-	6.8
Loturco et al.(54)	Male Soccer Age:23.9	7.9	-	-	-	-
DosSantos et al.(99)	Males Soccer - rugby - cricket Age: 21.8	-	-	7.25	-	6.42
Gonzalo-Skok et al.(104)	Male Soccer U17	6.8-8.9*	-	3.3-4.3*	-	4.0-4.7*

Note: Author's own review of the different magnitudes for inter-limb asymmetries obtained in unilateral jump tests.
*baseline test. CJM: countermovement jump; LJ: lateral jump; BJ: broad jump; DJ: drop jump; TH: triple hop.

Various studies have assessed asymmetries in change of direction tests, some of which are shown in Table 2. This action, as already mentioned, can be considered not only as one of the most functional skills, but also as one of the most complex, due to all the mechanisms involved. From this perspective, this table also shows the different scores assessed in distinct COD and CODD protocols. Different authors have notably used change of direction tests at different cutting angles to obtain the asymmetry magnitude (75,92,97,99).

Table 2. COD inter-limb asymmetries magnitude

Author	Sport	COD90º (%)	COD180º (%)	505-180º (%)	CODD (%)
Dos'Santos et al. (105)	Males Soccer -rugby - cricket Age: 20.0	-	-	-3.8	-
Fort-Vanmeerhaeghe et al.(74)	Female Basketball Age:15.6	-	-1.71	-	-
Dos'Santos et al.(99)	Males Soccer -rugby - cricket Age: 21.8	-4.93		-2.74	
Dos'Santos et al. (83)	Female Netball Age: 15.4	-	-	-2.81	-14.5
Bishopt et al.(67)	Female Soccer Age: 20.5	-	-	-2.39	-

Note: Author's own review of the different inter-limb asymmetry scores obtained in change of direction tests.
COD: Change of direction; CODD: change of direction deficit

The magnitudes of the inter-limb asymmetries observed in the COD tests can be seen to present some very low inter-limb asymmetry scores in comparison to those obtained in most of the jump tests, and especially the vertical jump test. These data suggest that the change of direction test is not sensitive enough to detect existing differences between limbs (inherent in the test). On the other hand, the CODD calculation (difference between COD and linear sprint performance) seems to be a good assessment method for detecting inter-limb asymmetries because it reveals a greater magnitude in the change of direction tests analyzed. Given the importance of the change of direction in multidirectional sports, Rouissi et al. (42) that further research is warranted in relation to assessing change of direction that is specifically focused on functionality and the different characteristics of this skill such as angles, phases of the change of direction, (acceleration, deceleration, moment of change of direction), and stimuli.

Variability of inter-limb asymmetries

As mentioned previously, the magnitudes of the asymmetries are markedly varied in the different tests administered. This is especially true of the variations in the jumps (70,103) and among the different COD and CODD values (83,99). The published works typically demonstrate weak relationships between the asymmetry indexes obtained in the different tests analysed (75,106), indicating that detecting asymmetries would appear closely related to the skill being assessed (55,106).

Discrepancies in the direction of asymmetries depending on the test were also observed. To this effect, Bishop et al. (55) assessed 28 amateur athletes in different jump tests (vertical, horizontal, lateral), observing that the dominant leg varied depending on the test. In another recent paper, Bishop et al. (103) recorded differences in the inter-subject directionality of the asymmetry among the different jump tests administered to U-17 footballers (countermovement jump, squat jump, drop jump) on force platforms. These studies showing the variability of the asymmetries given in the different tests carried out suggest the need to analyse and draw conclusions on an individual level, depending on the assessment of each skill (54,55,106).

Another aspect to consider when assessing asymmetries, also mentioned previously, is sport specificity. To this effect, the repetition of asymmetric patterns of play can influence the increase in the magnitudes of asymmetry (72,107). Similarly, the specific influence of the demands of the game can also influence asymmetry values, as observed when the different roles of the players in multidirectional sports were compared (108,109).

Lastly, another aspect studied that supports the variability of asymmetries between subjects, is their age and maturation stage. Bishop et al. (70) observed how greater asymmetries in the vertical jump were observed in young footballers (U16) than in older players. Furthermore, in a study which assessed asymmetries according to biological stage, also conducted with young footballers, Read et al. (110) observed how asymmetries may increase with degree of maturity. This variability could be attributed to the changes in neuromuscular strategies that occur in the PHV stage, coinciding with adolescence (22,23).

Inter-limb asymmetries and performance

Many studies have found how high levels of asymmetry can negatively influence performance (68). However, an optimal or negative threshold has not yet been established due to the variability and individual nature of asymmetries. For example, Bishop et al. (69) recently concluded that inter-limb asymmetries of ~12.5% in the unilateral countermovement jump (UCMJ) are associated with reduced jumping performance (r = -0.47 to -0.58) and speed in 5, 10, and 20m sprints in youth female soccer players. Bishop et al. (67) also showed how asymmetries in the drop jump are associated with reduced speed performance over 30m sprints and reduced COD performance 505 test in adult female soccer players. Similarly, Maloney et al. (97) showed how large inter-limb asymmetries in the drop jump are associated with reduced performance in COD (double COD90º) in healthy males. Figure 8 is a graphic representation of the negative effects observed in different papers in relation to performance of the different skills.

Despite the data presented here, not all studies have recorded a relationship between the asymmetry index and effect on performance in skills tests. Regarding jumping, Lockie et al. (93) found asymmetries of 10.4%, 3.3%, and 5.1% in the vertical, horizontal, and lateral jumps, respectively, among university athletes, without correlating these data with sprint (20m) and change of direction performance (505 test – T-Test). Likewise, Dos'Santos et al. (99) found inter-limb asymmetries of 7.25% in the single-leg hop test and 6.42% in the single-leg triple hop test, but found no relation in change of direction tests (COD90º - 505 tests).

Considering the existing degree of heterogeneity in the results of different studies analyzing the relationship between the amount of inter-limb asymmetry and the level of performance, future studies should be focused on the research of the optimal tests (according to the skills evaluated) to clarify this possible association.

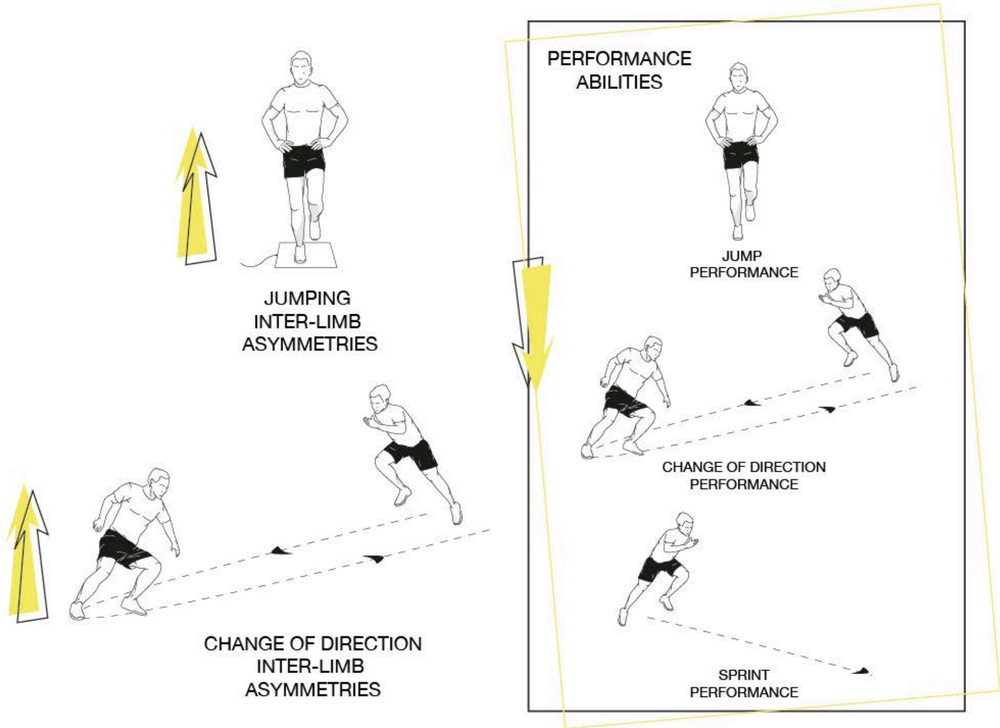


Figure 8: Effect of inter-limb asymmetries on jump, sprint, and change of direction performance.

This diagram demonstrates the proposed negative association of inter-limb asymmetries on the performance of different skills as described in the recent review (111).

Strength

Approach

The benefits of strength training have been widely studied in areas such as sports performance (112–114), and among the youth population (6,115,116). Despite the concerns raised by strength training in youth (often due to a lack of information) (117), the scientific and practical evidence demonstrates the benefits of this training for children and adolescents, among which are aspects related not only to bone health and body composition, but also to injury prevention (118,119) and improving sports performance (120). Lloyd et al. (12) addresses the subject of strength training and other skills training from a long-term perspective, determining these capacities at the different growth stages and indicating the potential benefits in terms of hypertrophy and muscle potential based on the PHV maturation stage. It is important that clear instructions are given to subjects in these first age groups, as is ensuring that the exercises are carried out correctly, in order to achieve better adaptations and reduce the likelihood injuries caused by their incorrect execution (117,121,122).

Below is a summary of strength work in youth when applying gravitational loads (what is usually defined as "traditional training") and iso-inertial loads. This is one of the methodological cornerstones of this doctoral thesis, and the point raised in this section will now be brought to a conclusion with two final paragraphs, one focused on comparing the two working methods (despite the paucity of literature to this effect), and the other aiming to show the functionality required in strength work.

Traditional resistance training

The effects of traditional resistance training have been widely studied in distinct populations, for example in youth (123) and in distinct sport disciplines (112–114,124). Hermassi et al. (112), for example, employed a combination of weightlifting and strength exercises (i.e. pull-over, snatches, bench press, clean and jerk) for 12 weeks to enhance performance in COD, 5m, 10m, 30m speed, squat jump, and three different handball throwing tests in male handball players. The greatest improvements were made in the squat jump and throwing speed. Gonzalo-Skok et al. (124) compare the effects of a 6-week bilateral and unilateral squat intervention in young basketball players (16 years old), showing that not only did the unilateral training have the greatest effect on jump, linear sprint, and COD ability, but it also reduced asymmetries.

Nonetheless, most of the tasks mentioned are of an analytical type, and although some authors classify them as "functional" they are in fact far removed from sport specific actions (125,126). This is also the case of studies analysing the effects of cable resistance training. In this case, the evidence showing strength improvement is so clear, but, in spite of the more functional possibilities that can give this kind of gravitational equipment, there are no training programs offering motor skills execution among their tasks.

Iso-Inertial training

Iso-inertial training, which aims to develop resistance to improve sport skills, has gained in popularity in recent years (127–130). Tesch et al. (131) suggests that one of the advantages of iso-inertial training is that resistance applied during eccentric phase of the movement, where the athlete is stronger, can be augmented relative to the concentric phase. Moreover, accommodating resistance can be applied during the concentric phase, more closely corresponding to the strength curve of the movement. Because of these attributes of iso-inertial training, beneficial effects of flywheel devices have been related to the peak force levels achieved during stretch-shortening cycles (132). This is supported by the different neuronal strategies found in concentric and eccentric phases when performing a stretch-shortening cycle (133), emphasizing the specific adaptations provoked by high intensity overload eccentric actions. These are different reasons because iso-inertial devices could lead to possible greater adaptations when comparing to gravitational load training, a less demanding eccentric work (131). Considering the nature of iso-inertial devices, Sabido et al. (134) suggest that the training load in these mechanisms will depend on the athlete's level, and they recommend to develop between 5 and 12 repetitions to have the possibility to maintain the maximum power emphasizing the eccentric overload.

There are different iso-inertial devices currently on the market (machines to do leg-curls, leg-extensions, squats, and leg presses, among others). Those known as the flywheel are comprised of a cylindrical structure that rolls up and unrolls the rope that transfers the resistance to the subject Figure 9. These devices allow some actions with a certain degree of functionality to be performed, despite they are not made to enable the execution of fundamental motor skills (131).

In addition, various studies have evidenced positive adaptations in performance with this type of device, for example Nuñez et al. (130) compared the effects of a 6-week programme of bilateral squats versus a unilateral lunge exercise with a flywheel device in 27 young male team sport players (22.8 years). Improvements were recorded in jumping (CMJ) and change of direction performance (COD90 and CODD90) in both groups (bilateral squat and unilateral lunge). However, the unilateral lunge exercise showed greater improvements in COD90, both in the dominant leg and the non-dominant leg, which suggests that the unilateral method may be more effective for improving change of direction performance.

In this line, Sabido et al. (135) to examined the addition of 7 weeks of extra training, that included squat and lunge actions with an eccentric load training, to a group of young handball players and compared this to a control group performing their normal training routine. The experimental group showed improvements in power in the half squat and the triple broad jump, although no improvements were observed in the vertical jump, 20m sprint, and throwing. Moreover, in a study of professional footballers (average age 24 years), Askling et al. (136) examined the efficacy of a 16 sessions of hamstring strength work (leg-curl) intervention led to performance improvements in the 30m sprint. Most of the studies showed no direct effects between the direction of intended force application in the exercises and the tests used.

Figure 9. Leg-curl with a flywheel iso-inertial device.
Example of iso-inertial type resistance with a wheel mechanism, in a specific hamstring exercise.

Another example of an iso-inertial device is the conical pulley, the characteristic feature of which is the conical shape of the structure where the rope that transfers the tension rolls up and unrolls (Figure 10). Due to its design, this type of device allows for a greater degree of movement than the flywheel, enabling more complex coordinative actions to be performed that better imitate specific sports skills. To this effect, several studies have shown the improvements achieved with these machines. In an 11-week intervention with young footballers (17 years), Tous-Fajardo et al. (127) compared a conventional workout and a functional workout combining eccentric overload (with the conical pulley, flywheel devices and vibration training). The authors reported that functional training programme conferred greater benefit to speed in the change of direction and the V-cut test performance versus traditional training. In the same research group, an 8-week training programme with young football players (20.5 years), Gonzalo-Skok et al. (128) compared an intervention consisting of a single bilateral squat exercise (vertical resistance) to a programme of 6 exercises specifically related to sport specific skills. Both interventions showed improvements in different functional performance measurements such as COD, linear sprinting and jumping. This study evidences how important the force vector application is when applied in relation to improving performance in the recorded functional tests.

Figure 10. Change of direction with a conical pulley iso-inertial device
Example of iso-inertial type resistance with a conical pulley, in a specific change of direction exercise.

Traditional resistance training vs iso-inertial training

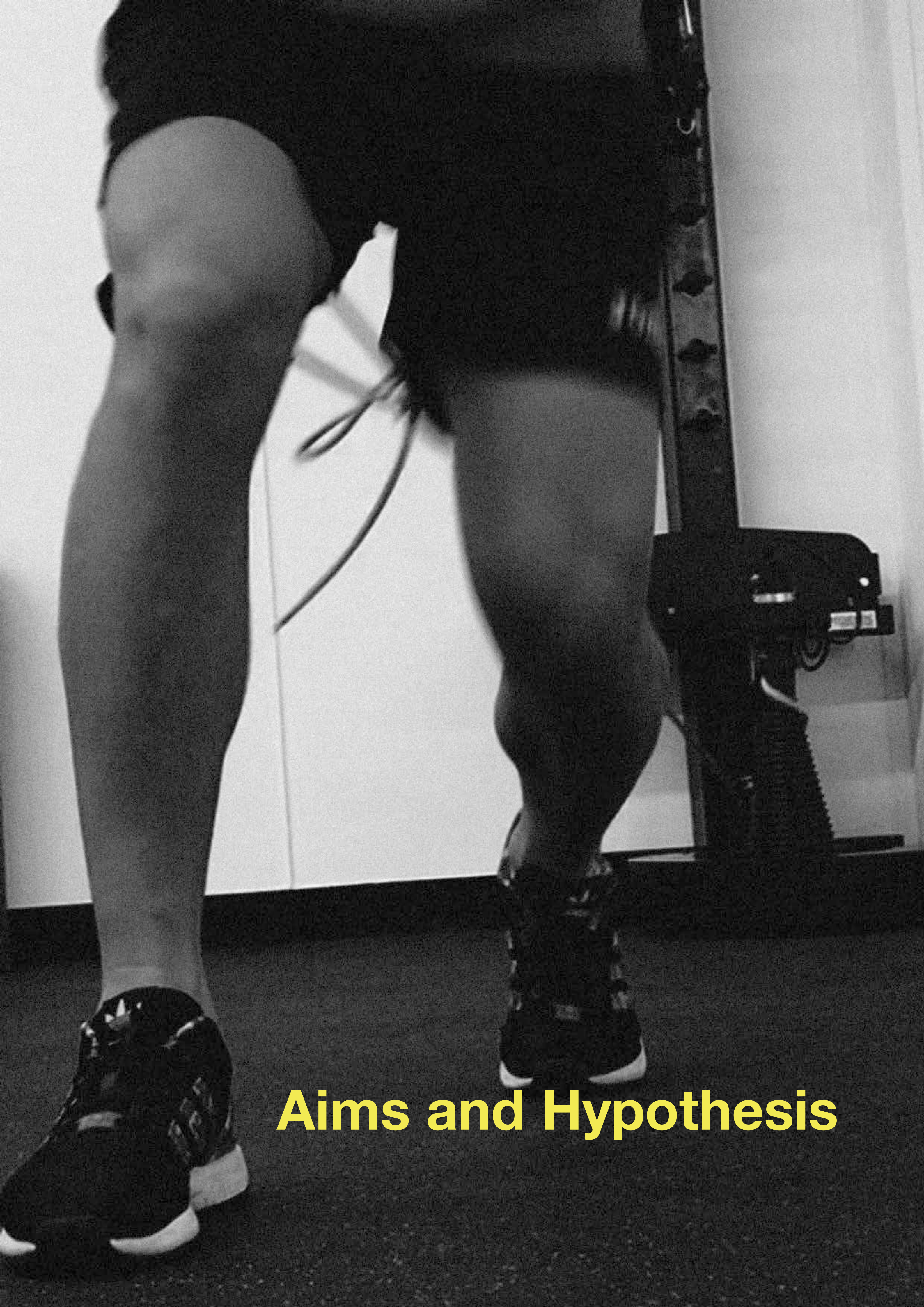
Several studies have compared the effects of resistance training with flywheel type iso-inertial devices and traditional resistance training (free weight training using gravitational resistance). Number of investigations have focused on the effects of muscular strength, the effects related to hypertrophy and performance-related parameters such as jumping and sprinting (137–140). This methodological comparison was addressed in two recent review articles (141,142) which drew very different conclusions. Based on the available literature, Vicens-Bordas et al. (142)

were unable to draw any firm conclusions about strength and hypertrophy. Whilst Maroto-Izquierdo et al. (141) conducted that high-intensity training with eccentric loads is associated with greater improvements in strength, power and hypertrophy in healthy, well-trained people. Moreover, this training was related to positive adaptations in sport performance such as improvements in the height of vertical jumps and sprint speed.

Few studies have analysed the effects of different methods with performance scores in different skills. In a recent study of professional handball players, Maroto-Izquierdo et al. (143) compared the two methods in a 6-week programme of flywheel leg press exercises. The authors reported greater effect in squat jump, UCMJ, T-Test, and linear speed performance tests. De Hoyo et al. (138) compared a half squat task in a 7-week traditional resistance training programme to front step task (acceleration action) in an iso-inertial resistance (conical pulley) programme. Despite comparing the direction of intended force application (bilateral versus unilateral nature of exercise selection) both groups showed performance improvements.
Considering the specialized literature, it is not possible to assert neither iso-inertial nor gravitational training is the most optimal methodology to increase motor skills performance. This is the reason to confirm the need of future research focused on the comparison of both methodologies.

Specificity

There are currently no studies comparing iso-inertial conical pulley and cable resistance training, and no proposals have focused on comparing tasks with a more specific and functional the direction of intended force application that enable resistance training to demonstrate a higher degree of correspondence to specific sports skills, despite the two devices mentioned providing freedom of movement and more ‘functional’ possibilities. Traditional strength proposals are not close to the specific demands of the sport, which are subject to dynamic environments (144). Furthermore, various current studies consider more ecological approach (145). The introduction of stimuli is fundamental for adjusting and adapting the tasks to real situations, as suggested by Young and Farrow (56) in a study which describes and classifies the introduction of specific and non-specific appropriate stimuli in the COD. One of the elements that has been described as a constraint to approximating the sporting reality is including the ball or racket into resistance training. To this effect, Moras et al. (146) observed improvements in the acceleration values, introducing the rugby ball in a coordinative action using an iso-inertial. In the same line, in a study of young soccer players, Milanović et al. (147) observed that introducing the ball places no limitations on improving agility performance in a speed, agility and quickness programme training, and that this could even be considered as a motivational element. For their part, Wdowski et al. (148) attribute the benefits in sprint performance of introducing the field hockey stick to athletes' kinetic responses (hip joint at the onset of the stance phase, maximum flexion of the knee joint during mid-swing) in relation to sport specific skills. These investigations are indicating a challenging field of study focused on the introduction of specific stimulus and situations in the resistance training, with the intention of knowing the effects may have these interventions on motor skills performance.



Aims and Hypothesis

General aim

To deepen in the existing knowledge relating lower inter-limb asymmetries and the assessment of motor skills performance in youth population of coordinative sports.

Specific aims

1) To quantify inter-limb asymmetries in performance tests (jumping, CODS, sprints, and muscle power tests) previously associated with multidirectional sports performance.

2) To analyze the validity of functional iso-inertial tests to evaluate inter-limb asymmetries.

3) To establish the relationships between the inter-limb asymmetries and performance in within performance tests.

4) To compare iso-inertial versus gravitational resistance training in order to elucidate the best methodology to reduce inter-limb asymmetries and increase motor skills performance.

Hypothesis

It was hypothesized that inter-limb asymmetries are multidependent on maturity, the sport, and the skills tested. Related to the assessment of change of direction, greater asymmetry values were expected when isolating and applying resistance during the assessment in comparison to the COD speed tests. Given that several investigations have purported a negative association between asymmetry and performance, it was further hypothesized that a similar relationship would be observed in this thesis. Lastly, it was hypothesized that iso-inertial training programme would result in a larger reduction of asymmetry and elicit greater performance benefits in comparison to cable-based resistance training program.

Methods

Five studies were carried out to test the thesis hypotheses, four of them cross-sectional studies (Studies 1-4) and one randomized-controlled trial (RCT) (Study 5).

In the following section, data related to the publications of the above-mentioned studies are presented, including summaries of the studies and a copy of the actual papers. This set of studies comprises the main body of this doctoral thesis. The manuscripts are featured in the chronological order in which they were written.

Publications

STUDY 1 Open access

Effects of Maturation on Lower Limb Neuromuscular Asymmetries in Elite Youth Tennis Players

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Article

Effects of Maturation on Lower Limb Neuromuscular Asymmetries in Elite Youth Tennis Players

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Abstract: Neuromuscular asymmetries have been previously associated with reduced performance. Similarly, maturation has shown that youth athletes may experience a loss of motor control, which could also lead to compromised physical performance. The present study aimed to evaluate and quantify the level of asymmetry among chronological and maturational groups. Forty-one youth tennis players performed the single leg countermovement jump (SLCMJ), star excursion balance test (SEBT) and a change of direction speed (CODS) test. Differences were found between the strongest and weakest limbs across all tests ($p < 0.001$), and also for SEBT in the posteromedial direction ($p = 0.02$), SEBT composite score ($p < 0.01$) in maturation groups, and for SEBT posterolateral direction ($p = 0.03$) and SEBT composite score ($p = 0.01$) in chronological groups. The SLCMJ showed the largest inter-limb asymmetries for the circa peak height velocity (PHV) group (19.31 ± 12.19%) and under-14 (U14) group (17.55 ± 9.90%). Chronological and maturation groups followed similar trends for inter-limb asymmetries, but the biological index showed larger asymmetry scores in the jumping test at PHV compared to that found in the chronological group (U14). These results show that inter-limb differences may be heightened during PHV. Practitioners can use this information to inform the decision-making process when prescribing training interventions in youth tennis players.

Keywords: inter-limb differences; vertical jump; balance; change of direction

1. Introduction

Tennis is an intermittent sport characterized by repetitive high-intensity efforts (e.g., accelerations, decelerations) during competition with an average duration of 90 min per match [1]. Thus, the development of multiple physical qualities [2] is essential for a tennis players' athletic development. More specifically, acceleration and braking skills are key characteristics in tennis performance and require a combination of musculoskeletal, neural, and coordinative components simultaneously [3]. It should also be noted that tennis players perform more actions on their forehand side [4], and due to the repetitive sport-specific demands, this represents an intrinsic risk factor for potential injuries [5].

Therefore, the development of lower limb asymmetries should be expected and taken into consideration in any injury prevention strategy in tennis.

Recent evidence has shown that larger asymmetries are a key factor to consider in the return to play process after injury [6], are linked to reduced neuromuscular control during hopping tasks [7], and have a detrimental effect on measures of physical performance [8,9]. Recently, Bishop et al. [8] showed that greater lower-limb asymmetries in jump height were associated with reduced 5, 10, 20 m sprint and vertical jump performance in youth female soccer athletes. Furthermore, Sannicandro et al. [9] showed that young soccer players (mean age = 11.2 years) displayed inter-limb asymmetries in the lateral hop test (18.5%), which was notably larger than that of the single or triple hop tests, and greater ($p < 0.05$) than that of younger players (mean age = 9.1 years). Thus, since asymmetries have been shown to be associated with reduced physical performance and potentially increase as youth athletes approach maturation, further research is warranted on the interaction between asymmetry and maturation in youth athletic populations.

In tennis, movements, such as change of direction speed (CODS) are frequently required [4], and given the unlikely nature of this high-intensity action occurring an equal number of times on each limb, will likely contribute to the development of neuromuscular asymmetries over time [10]. To the authors' knowledge, only one previous study has investigated the presence of lower-limb neuromuscular asymmetries in strength and speed tasks in youth tennis athletes [11]. These authors used a six-week training intervention consisting of lower limb balance and strength-based exercises performed twice a week. Results showed a reduction in asymmetry during the single hop (9.0 to 3.7%; $p < 0.001$), lateral hop (10.8 to 3.2%; $p < 0.001$), and CODS (7.2 to 2.7%; $p < 0.05$) tests. While useful, this study did not take into consideration the maturation levels of players; thus, it is possible that such analysis would have resulted in altered between-limb differences, given the changes in motor control during these stages of development [12].

Differences in the morphological profiles of young tennis players and how these values can affect coordinative abilities have been identified among chronological age categories [13], especially during adolescence, which is one of the most vulnerable times when youth athletes may be subject to injury [14]. Van der Sluis et al. [14] recorded 178 injuries during three years among 26 youth soccer players (82% in the lower limbs), being higher in the peak height velocity (PHV) group in comparison to the pre-PHV and post-PHV groups. This can be explained by the negative effects on neuromuscular control that occur during PHV [15–17].

Therefore, the aims of the present study were: 1) to quantify the lower-limb asymmetry profile in youth tennis players through different tests (e.g., jump, dynamic balance, and CODS) and, 2) to differentiate the level of asymmetry between maturational stages and chronological groups in youth tennis athletes. It was hypothesized that youth tennis players would show increased asymmetry when grouped by maturational stages compared to chronological groups, with the largest inter-limb differences seen circa-PHV.

2. Material and Methods

2.1. Study Design

The present study used a battery of fitness tests: single leg countermovement jump (SLCMJ), star excursion balance test (SEBT), and CODS to determine the inter-limb asymmetries of youth tennis athletes. The sample was divided according to their chronological age in U18, U16, U14, U12 and maturational stages in pre-PHV, circa-PHV, and post-PHV, enabling a comparison to be drawn across age groups for physical performance and between-limb differences. All tests were conducted on the same day and in a randomized order, with players required to attend a familiarization session beforehand to understand the test protocols. During the familiarization session, athletes were allowed to practice the tests an unlimited number of times, until a satisfactory level of technical competence had been reached, while being monitored throughout. All athletes were asked to continue with their normal dietary and sleeping habits and refrain from any strenuous physical activity for 24-h prior to the test day.

2.2. Participants

Forty-one elite tennis players volunteered to participate in the present study, with their anthropometric data re shown in Table 1. Participants were excluded if they had incurred an injury over the three months before testing procedures. Written informed consent and assent were signed by participants and their parents or guardians (for those under 18). All volunteers were informed of possible risks and benefits related to the intervention process. The study was approved by the Catalan Sports Council Ethics Committee (07/2017/CEICGC). The experimental protocol was in accordance with the Declaration of Helsinki for the study of human subjects.

Table 1. Descriptive characteristics of the participants (n = 41).

	Total (n = 41)	Post-PHV (n = 20)	Circa PHV (n = 13)	Pre-PHV (n = 8)
Chronological age (years)	14.6 ± 2.7	16.4 ± 1.5	14.2 ± 1.3	10.5 ± 1.9
Peak height velocity (PHV) *	0.8 ± 2.3	2.6 ± 1.1	0.2 ± 0.4	−2.9 ± 1.2
Training experience (years)	6.6 ± 3.3	8.6 ± 2.9	5.2 ± 2.7	3.7 ± 1.6
Height (m)	1.67 ± 0.10	1.75 ± 0.10	1.67 ± 0.80	1.46 ± 0.10
Body mass (kg)	56.3 ± 13.3	65.0 ± 10.1	54.2 ± 6.3	38.1 ± 8.5
BMI (kg/m^2)	20.0 ± 2.1	21.2 ± 1.9	19.5 ± 1.2	17.7 ± 1.8
Height seated (cm)	83.3 ± 7.0	87.7 ± 5.0	82.7 ± 3.3	73.1 ± 4.4
Length leg (cm)	91.6 ± 8.1	95.0 ± 6.1	93.0 ± 4.9	80.5 ± 7.2

Data shown as mean ± SD. * Estimation of biological age [18].

2.3. Procedures

Prior to the experimental session, all players performed a standardized 10-min warm up. This consisted of dynamic stretches, such as multi-planar lunges, inchworms, bodyweight squats, and spidermans and practice trials for all test protocols. Each test was practiced three times at 60, 80, and 100% of each athlete's perceived maximum effort. A three-minute rest period was prescribed between the warm up and the first test. Jump and balance testing were performed indoors, and the CODS testing was performed on an outdoor tennis court (hard surface).

The sample was divided according to their chronological age in U18, U16, U14, U12 and maturational stages in pre-PHV, circa-PHV, and post-PHV. To calculate the biological age, four variables were registered for every subject: chronological age, stature, sitting height, and body mass. These variables were used to calculate the PHV following the formula proposed by Mirwald et al. [18]. Early maturing (pre-PHV), defined as preceding the average age of PHV by 1 year; average maturing (circa-PHV), ±1 year from PHV; and late maturing, greater than 1 year after PHV (post-PHV).

2.3.1. One Hundred and Eighty Degree Change of Direction Speed (CODS) Test

Subjects were instructed to perform a single 180° CODS, for a total distance of 10 m, with the CODS occurring after a distance of 5 m (Figure 1A). Total time during the CODS test was measured with infrared beams from photocells, placed on the starting line and connected to a computer (Chronojump Boscosystem, Barcelona, Spain). The fastest time of the three trials for each leg was used for data analysis. Each trial was separated by a 60-s recovery period. A trial was considered successful if the entire foot passed the line while changing direction.

2.3.2. Single Leg Countermovement Jump (SLCMJ)

Subjects were instructed to stand on one leg with the hands on hips, and the alternating leg flexed to approximately 90° at the hip and knee. Upon instruction, subjects were instructed to perform a countermovement to a self-selected depth before accelerating as fast as possible into a vertical jump (Figure 1B). The trial was disregarded and repeated if the subject was helped by the impulse of the opposite leg, did not keep the jumping leg fully extended during the flight phase of the jump or if hands came off the hips. Three successful trials per limb were collected in a randomized order. Each trial was separated by a 60-s recovery period. The height in centimeters was calculated by a contact mat system (Chronojump Boscosystem, Barcelona, Spain). The highest jump for each leg was recorded and used for subsequent data analysis.

2.3.3. Star Excursion Balance Test (SEBT)

The SEBT was performed with socks on the feet as described by Overmoyer et al. [19] in three specific directions (anterior [A], posteromedial [PM], and posterolateral [PL]) (Figure 1C). The distal aspect of the subject's big toe was centered at the junction of the grid. While maintaining a single-leg stance, the subject was asked to reach lightly with the contralateral leg in the three specific directions with hands placed on hips at all times. The maximal reach distance was measured at the point where the most distal part of the foot touched the line. The trial was disregarded and repeated if the subject failed to maintain a unilateral stance, lifted or moved the stance foot from the grid, touched down with the reach foot, or failed to return the reach foot to the starting position. The greatest reach (in centimeters) of three for each direction was used for data analysis. With these three scores, the total value of the test was calculated for these authors, using the following formula taking into account the length (cm) of the leg (LL): $\{[(A + PM + PL)/(LL \times 3)] \times 100\}$ = SEBT composite [19].

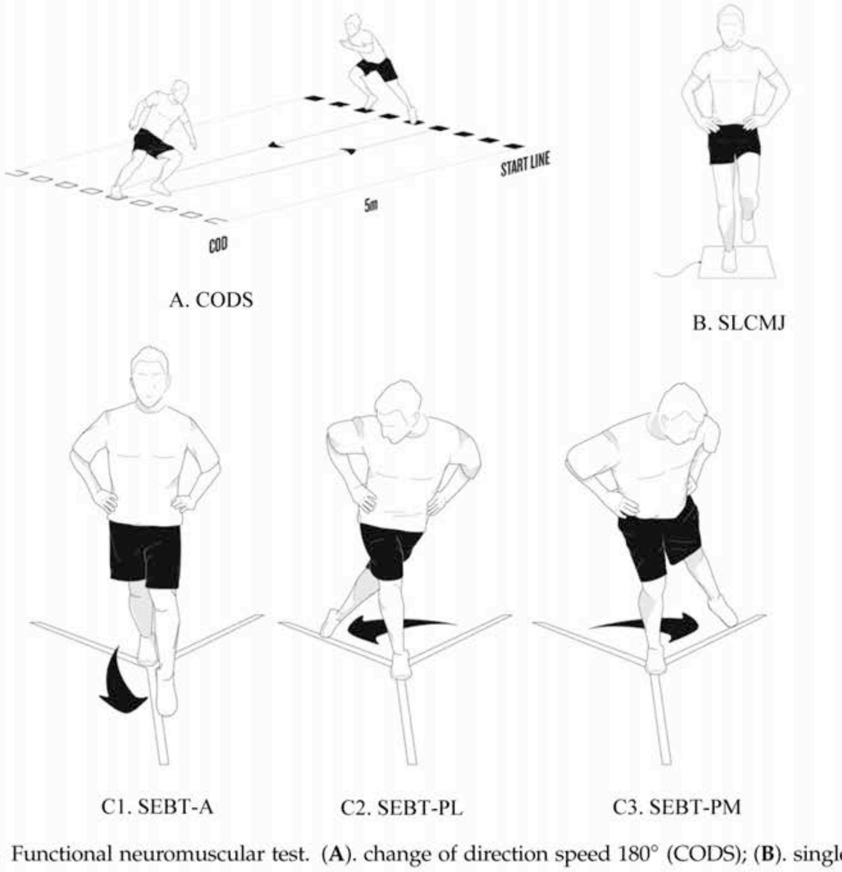

Figure 1. Functional neuromuscular test. (**A**). change of direction speed 180° (CODS); (**B**). single leg countermovement jump (SLCMJ); (**C1**). star excursion balance test anterior (SEBT-A); (**C2**). star excursion balance test posterolateral (SEBT-PL); (**C3**). star excursion balance test posteromedial (SEBT-PM).

2.4. Statistical Analysis

The Kolmogorov–Smirnov test was applied to determine whether data sets were normally distributed. The absolute values of the tests were normally distributed, whereas inter-limb asymmetry values were not; thus, they were log-transformed before subsequent statistical analysis. Paired samples *t*-tests were used to detect performance differences between the strongest and weakest limbs for the whole sample, introducing each test performance absolute values as dependent variables. Cohen's *d* effect sizes were performed on pairwise comparisons which were computed as the mean difference divided by the pooled standard deviation and interpreted as: small (<0.2), moderate (0.2–0.5), and large (>0.8) mean differences [20]. The lower and upper limits for 95% confidence intervals (CI) were presented for the sample mean difference of each task when a pairwise or main effect comparison was detected.

Analysis of covariance (ANCOVA) was used to examine PHV between-group asymmetries for all neuromuscular capacities assessed, controlling for gender (the inter-limb asymmetry index for each test was introduced as the dependent variables, whereas the PHV groups were included as the independent variable). Partial Eta squared (η^2p) scores were calculated as measures of size effect for all ANCOVA effects, where <0.01 = trivial; 0.01 to 0.06 = small; 0.06 to 0.14 = medium, and >0.14 = large [21]. The level of significance was set at $p < 0.05$. All the analyses were performed using IBM SPSS Statistics for Windows version 22.0 (IBM Corp, Armonk, NY, USA). Finally, to calculate inter-limb asymmetry between legs, the following formula was used: [(strongest−weakest/strongest) × 100] [22].

3. Results

Performance differences in each test between limbs for the whole sample are presented in Table 2. Differences between strongest and weakest limbs were found across all tasks ($p < 0.001$). Mean values of asymmetry showed that the SLCMJ test produced the largest between-limb differences (14.7%), whereas the CODS test showed the lowest percentage of asymmetry (2.1%). Inter-limb differences in all other tests ranged between 3.5 and 5.5%.

Table 2. Strongest and weakest limbs performance of each test for the whole sample of tennis players (n = 41).

	Strongest	Weakest	Mean Difference (95% CI)	Asymmetry (%)	*p* Value	ES
SLCMJ (cm)	14.55 ± 4.87	12.33 ± 4.46	2.05 (1.58 to 2.51)	14.71 ± 10.05	<0.001	0.48
SEBT-A (cm)	76.99 ± 7.51	73.31 ± 7.48	3.68 (2.90 to 4.45)	4.76 ± 3.16	<0.001	0.49
SEBT-PM (cm)	114.21 ± 9.14	109.37 ± 9.51	4.84 (3.56 to 6.10)	4.22 ± 3.54	<0.001	0.52
SEBT-PL (cm)	108.33 ± 8.61	102.39 ± 9.17	5.94 (4.58 to 7.29)	5.49 ± 3.95	<0.001	0.67
SEBT composite (cm)	99.16 ± 7.05	95.71 ± 7.34	3.46 (2.75 to 4.16)	3.49 ± 2.29	<0.001	0.48
CODS (sec)	2.78 ± 0.23	2.85 ± 0.24	0.08 (0.06 to 0.09)	2.09 ± 2.24	<0.001	0.30

CI: confidence intervals; ES: Cohens' *d* effect size; SLCMJ: single leg countermovement jump; SEBT-A: star excursion balance test anterior; SEBT-PM: star excursion balance test posteromedial; SEBT-PL: star excursion balance test posterolateral; CODS: change of direction speed 180°. Performance differences in each test between limbs for the whole sample were assessed by paired *t*-test.

Mean values of asymmetry for each functional performance test according to chronological age are shown in Table 3. The between-group analysis showed differences with large age effects for the asymmetry scores of SEBT-PL ($F = 3.35(3,36)$; $p = 0.03$; $\eta^2p = 0.22$) and SEBT composite ($F = 4.01(3,36)$; $p < 0.01$; $\eta^2p = 0.25$). Post-hoc analyses showed that SEBT-PL and SEBT composite asymmetries decreased with age since U12 group had higher mean asymmetry values compared to the U16 group (respectively: 9.67 ± 3.79% vs. 4.07 ± 3.66%, CI = 0.85–2.44, $p = 0.03$ and 6.09 ± 2.14% vs. 2.13 ± 1.49%, CI = 0.19–1.85, $p < 0.01$). CODS, SEBT-PL, SLCMJ, SEBT-A, and SEBT-PL did not show differences statistically between-groups (all $p > 0.05$). The biggest asymmetries found was related to jumping action (SLCMJ) in all age groups (12–17%).

Table 3. Asymmetry index between legs profile by chronological groups.

	U18 (*n* = 12)	U16 (*n* = 13)	U14 (*n* = 10)	U12 (*n* = 6)	F	*p* *	η^2p
SLCMJ	12.34 ± 7.72	15.31 ± 11.64	17.55 ± 9.90	13.43 ± 11.94	$0.71_{(3,36)}$	0.55	0.06
SEBT-A	4.21 ± 2.31	3.30 ± 2.34	6.01 ± 3.28	6.89 ± 4.55	$2.60_{(3,36)}$	0.07	0.18
SEBT-PM	2.94 ± 3.45	3.82 ± 3.46	5.37 ± 3.50	5.74 ± 3.69	$1.66_{(3,36)}$	0.19	0.12
SEBT-PL	4.53 ± 3.47	4.07 ± 3.66	5.70 ± 3.54	9.67 ± 3.79 ^	$3.35_{(3,36)}$	0.03	0.22
SEBT composite	3.28 ± 1.56	2.13 ± 1.49	3.99 ± 2.73	6.09 ± 2.14 ^	$4.01_{(3,36)}$	0.01	0.25
CODS	1.31 ± 1.21	2.21 ± 2.89	2.52 ± 2.24	2.69 ± 2.36	$1.44_{(3,36)}$	0.25	0.11

* Significantly different between subjects analyzed by ANCOVA; ^ significantly different from U16 ($p < 0.05$). SLCMJ: single leg countermovement jump; SEBT-A: star excursion balance test Anterior; SEBT-PM: star excursion balance test posteromedial; SEBT-PL: star excursion balance test posterolateral. CODS: change of direction speed 180°; η^2p: partial eta-squared.

Mean values of asymmetry for each functional performance test according to maturational status are shown in Table 4. The between-group analysis showed differences with large maturational stage effects for the asymmetry scores of SEBT-PM (F = 4.53(2,37); $p = 0.02$; $\eta^2p = 0.20$) and SEBT composite (F = 6.02(2,37); $p < 0.01$; $\eta^2p = 0.24$). Post-hoc analyses showed that SEBT-PM and SEBT composite asymmetries decreased with increasing maturational stage. Pre-PHV group had higher mean values of asymmetry in SEBT-PM in comparison to post-PHV (6.94 ± 3.53% vs. 2.87 ± 3.12%, CI = 0.94–7.19, $p = 0.01$). In addition, the pre-PHV group had higher mean values of asymmetry in SEBT composite in comparison to the post-PHV and circa PHV groups (6.08 ± 1.82% vs. 2.97 ± 1.49% CI = 1.51–4.70; $p = 0.001$ and 2.73 ± 2.57% CI = 1.33–5.36, $p = 0.003$). CODS, SLCMJ, SEBT-A, and SEBT-PL did not show statistically differences between-groups (all $p \geq 0.05$), but SEBT-PL was at the limit for significance ($p = 0.05$). The highest asymmetry found was related to jumping action (SLCMJ) in all maturational stage groups (12–19%), with the larger value in circa PHV group (19.31 ± 12.19).

Table 4. Asymmetry index between legs profile by maturational stage groups.

	Post-PHV (*n* = 20)	Circa PHV (*n* = 13)	Pre-PHV (*n* = 8)	F	*p* *	η^2p
SLCMJ	12.53 ± 7.17	19.31 ± 12.19	14.49 ± 10.93	$1.27_{(2,37)}$	0.29	0.06
SEBT-A	4.12 ± 2.56	5.52 ± 4.19	5.27 ± 2.55	$0.80_{(2,37)}$	0.46	0.04
SEBT-PM	2.87 ± 3.12	4.63 ± 3.32	6.94 ± 3.53 ^	$4.53_{(2,37)}$	0.02	0.20
SEBT-PL	4.21 ± 3.29	5.79 ± 4.61	7.98 ± 3.45	$3.13_{(2,37)}$	0.05	0.14
SEBT composite	2.97 ± 1.49	2.73 ± 2.57	6.08 ± 1.82 ^ #	$6.02_{(2,37)}$	<0.01	0.24
CODS	1.12 ± 1.30	2.83 ± 3.02	3.18 ± 1.91	$1.96_{(2,37)}$	0.16	0.09

* Significantly different between subjects analyzed by ANCOVA; ^ significantly different from Post-PHV ($p < 0.05$) and # significantly different from PHV after Bonferroni adjustment ($p < 0.01$). SLCMJ: single leg countermovement jump; SEBT-A: star excursion balance test anterior; SEBT-PM: star excursion balance test posteromedial; SEBT-PL: star excursion balance test posterolateral. CODS: change of direction speed 180°; η^2p: partial eta-squared.

4. Discussion

The present study aimed to quantify inter-limb asymmetries in jump, balance, and CODS tests and to differentiate the level of asymmetry between chronological and maturational groups in elite youth tennis players. Differences were found among groups only in the SEBT, both in maturational and chronological groups, indicating a lack of results to confirm our previous hypothesis. As such, maturational stages cannot differentiate larger levels of asymmetry among youth tennis players when comparing to a chronological division of this population. Despite these results, there are some important aspects requiring further discussion.

Larger asymmetries in SEBT composite were found in pre-PHV and U12 groups (~6%). These values were considerably higher than those found in adults [19] and youth female basketball players post-PHV [23]. Both chronological and maturational analysis showed a marked trend to detect larger asymmetries before and during PHV (U12 and U14 groups when considered chronologically). This tendency of balance asymmetry to decrease with maturation is similar to those previously reported in youth soccer players [24]. The SEBT assesses balance through the demand of forced positions, which also requires high levels of strength in the supporting limb to allow better scores [25]. Considering these results, SEBT can be considered a useful assessment tool to detect inter-limb asymmetries. Despite this, it should be acknowledged that this test is not entirely representative of the sporting actions which occur in tennis.

Greater asymmetries were found in the SLCMJ compared to the SEBT and CODS tests, and were also found when differentiating between groups both ways (i.e., maturational and chronological). This is in agreement with recent studies in other sporting populations [8,25,26]. The greater asymmetries of this test were found in circa-PHV (~19%), similar to the maturation stages comparison found in elite youth soccer [24]. Although the SLCMJ test appears to be the most sensitive test at detecting asymmetries, and is in agreement with previous research [8,25,26], it is necessary to have a critical perspective if we want to consider this value as a risk factor for injury or reduced sporting performance. Given the prevalence of lateral movements in tennis [4], tests which aim to determine functional deficits in performance in this plane of motion must also be considered, such as CODS tests.

In contrast, the CODS test revealed the lowest level of asymmetry, also in agreement with previous studies of 1.21% in female youth basketball players [23] and 2.74% in male team sport athletes [27]. In the present study, it is important to point out the biggest magnitude of asymmetry in this test was when maturational analysis was applied, specifically in the pre-PHV group. However, this value was still very small (3.18 ± 1.91), highlighting that total time may be a poor metric when looking to detect existing side-to-side differences. When considering chronological age, the U12 and U14 groups showed even lower values (2.69 ± 2.36 and 2.52 ± 2.24, respectively) than the pre-PHV and PHV groups (3.18 ± 1.91 and 2.83 ± 3.02, respectively); thus, all groups showed near perfect symmetry when using total time as a means of quantifying asymmetry. Consequently, practitioners should consider alternative test methods when looking to detect inter-limb asymmetry during CODS actions. For example, strategy-based metrics associated with CODS performance could be considered which aim to isolate the change of direction actions themselves [28]. Furthermore, during maturation, youth athletes can enhance power and speed qualities; however, this is frequently accompanied by a decrease in neuromuscular control [29]. This evidence supports the importance of neuromuscular control training [30] to reduce asymmetry, which has been suggested in previous studies [8,24].

This study was not without some limitations. First, the pre-PHV and U12 groups had a low number of subjects (n = 8 and n = 6, respectively), which in turn may have impacted the statistical power of some of the analyses. Comparing inter-limb asymmetry scores across multiple tests and chronological and maturational groups is scarce; thus, the present study helps to build on a relatively unexplored area of the literature. However, future research should aim to establish larger group sizes where possible, which may provide normative data for asymmetry at different stages of maturation. Second, although useful for the sport of tennis, these results can only be attributed to this sport. Recent research has highlighted the individual nature of asymmetries [31]; thus, practitioners are encouraged to calculate existing imbalances in their own population of athletes to determine its relevance to performance and potential injury risk.

5. Conclusions

Taking into consideration our results, we can conclude that chronological and maturational analysis of inter-limb asymmetries did not show different results when studying inter-limb asymmetries. When analyzing specific tests, we can detect interesting aspects when maturational stages are studied in comparison with chronological groups. Second, the SLCMJ showed the greatest magnitude of asymmetry and can be considered a useful test when aiming to detect between-limb imbalances. Third, it is necessary to develop more accurate analyses of CODS tests, given that total time appears to be a poor metric for detecting asymmetry. Finally, the largest values of neuromuscular asymmetries were shown in pre-PHV/U12 and in circa-PHV/U14, highlighting SLCMJ in circa-PHV/U14.

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STUDY 2

Jumping-based Asymmetries are Negatively Associated with Jump, Change of Direction, and Repeated Sprint Performance, but not Linear Speed, in Adolescent Handball Athletes

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Abstract study 2

The aim of the present study was to determine the association of multi-directional jumping asymmetries with measures of physical performance. Forty-two handball athletes (age: 15.96 ± 1.3 years; height: 174.11 ± 7.3 cm; body mass: 70.49 ± 13.3 kg) performed a mid-season fitness test battery consisting of single leg countermovement, lateral and broad jump tests, two change of direction speed (CODS) tests, an 8 x 10m repeated sprint test, and a 20m sprint. The Kappa coefficient showed only 'slight' levels of agreement (K range = -0.05 to 0.15), indicating that asymmetries rarely favoured the same side during each of the jump tests. The single leg countermovement jump showed significantly ($p = 0.006$) larger asymmetries (11.2 ± 8.4) than the broad jump (6.4 ± 4.6) and significant correlations were present between jumping asymmetries and jump ($r = -0.32$ to -0.52), CODS ($r = 0.31$ to 0.32) and repeated sprint ($r = 0.35$ to 0.40) performance. The findings of the present study highlight the independent nature of jumping asymmetries and associations with measures of physical performance. Practitioners are encouraged to use multiple tests to detect existing side differences and consider appropriate training interventions for the reduction of inter-limb asymmetries.

Key Words: Handball, inter-limb differences, performance reduction

INTRODUCTION

Inter-limb asymmetries refer to the performance or function of one limb in relation to the other (Bishop et al., 2018b) and has been a common line of investigation in recent years with numerous methods employed to detect their prevalence. For example, asymmetries in strength have been reported during the back squat (Sato and Heise, 2012), isometric squat and mid-thigh pull (Dos'Santos et al., 2018; Hart et al., 2014; Thomas et al., 2017), and isokinetic dynamometry (Costa et al., 2015; Ruas et al., 2015). Jump tests have also been commonly used to detect between-limb differences with the countermovement jump (CMJ), broad jump (BJ), and drop jump (DJ) frequently used in addition to their unilateral variations (Bishop et al., 2018c; Hoffman et al., 2015; Lockie et al., 2014; Maloney et al., 2017; Meylan et al., 2009). Further to this, between-limb asymmetries have also been measured in sprinting (Exell et al., 2012; Haugen et al., 2018), change of direction speed (CODS) tasks (Dos'Santos et al., 2018, Madruga-Parera et al., 2019a) and balance (Madruga-Parera et al., 2019b) and highlighting the versatility of physical performance tests that can be used to detect inter-limb asymmetries. Although useful, reporting their prevalence alone does little to further our understanding of whether their reduction is needed. For this, investigations into the effects of asymmetries on physical performance represent a useful starting point in understanding their importance (Bishop et al., 2018d; Bishop et al., 2019; Madruga-Parera et al., 2019a; Maloney, 2018).

When looking at the effects on performance, jump testing has been a common line of investigation, most likely because of its time-efficient nature and relatively easy test procedures (Bishop et al., 2017). Hoffman et al. (2007) reported jump height asymmetries from the single leg CMJ (SLCMJ) of 9.7% in 62 college football players;

however, no significant relationships were reported with the L-run CODS test. These findings are supported in other research (Dos'Santos et al., 2018; Lockie et al., 2014). Lockie et al. (2014) highlighted the test-specific nature of asymmetries by reporting asymmetries of 10.4% (jump height from SLCMJ), 3.3% (jump distance from single leg BJ [SLBJ]) and 5.1% (jump distance from single leg lateral jump [SLLJ]). No meaningful correlations were found when compared to a 20m sprint, the 505 or modified t-tests. Dos'Santos et al. (2017) reported jump distance asymmetries of 6.25 and 5.69% in the single leg and triple hop tests respectively, and again, showed no associations with two CODS tests. Similarly, Dos'Santos et al. (2018) reported no significant correlations between strength asymmetries during an isometric mid-thigh pull and performance during 180° and 90° cutting actions.

In contrast, Maloney et al. (2017) used the single leg DJ to assess side-to-side differences in jump performance and compare to CODS performance. Results highlighted that faster athletes during the CODS task showed asymmetries in jump height of only 2.4%, whereas slower athletes were significantly more asymmetrical (7.2%). In addition, jump height asymmetry was associated with slower CODS performance (r = 0.60). More recently, Bishop et al. (2018c) quantified asymmetries from the SLCMJ, single, triple and crossover hop tests for distance in elite youth female soccer players. Results showed that jump height asymmetries (from the single leg CMJ) were negatively associated with sprint performance (r = 0.49 to 0.59), noting that a positive correlation is indicative of slower times. Furthermore, asymmetries during the triple hop test were associated with reduced horizontal jump performance (r = -0.47 to -0.58) and jump height asymmetries were also negatively associated with jump height (r = -0.47 to -0.53).

Owing to the conflicting findings in the literature, further research is warranted to determine whether asymmetries are truly associated with decrements in physical performance. Therefore, the primary aim of the present study was to determine the effects of inter-limb asymmetries on measures of physical performance. In addition, previous literature has shown the task-specific nature of asymmetries; thus, a secondary aim was to assess the consistency of how frequently each asymmetry score favoured the same side (*i.e.,* left or right). This would provide a more in-depth picture of the task-specific nature of asymmetries, rather than just reporting different percentage values alone.

Methods

The present study conducted a mid-season fitness testing battery on a group of elite adolescent handball athletes over the course of two consecutive days. Handball is an intermittent, high intensity sport characterised by multiple accelerations, decelerations, changes of direction and ballistic jumping movements (Póvoas et al., 2017); thus, the selected tests represented ecologically valid criteria for the present sample.

Participants

Forty-two youth male handball players (age: 16.0 ± 1.3 years; height: 174.1 ± 7.3 cm; body mass: 70.5 ± 13.3 kg), were recruited from a handball club in Barcelona. Players had a minimum of seven years of experience playing competitive handball (Catalan Handball Federation), consisting on average of three handball training sessions per week. Participants were excluded if they suffered any injury either at the time or during three months prior to testing. Written informed consent was obtained from each participants' parents or guardians, owing to their age. This study was approved by the Catalan Sports Council Ethics Committee.

Design and Procedures

Testing was performed over two consecutive days. Day one consisted of three unilateral jump tests, two CODS tests and a 20m sprint test. On day two, the players performed the repeated sprint test which consisted of 8 x 10m sprints. The 8 x 10m repeated sprint was performed on the second day owing to the likelihood of it impacting the performance of other tests if conducted on the same day. Each subject went through a specific warm up procedure consisting of five minutes light jogging at approximately 40-50% of the maximum perception of individual effort (indicated verbally) and 2 sets of 6 repetitions of dynamic stretches for the lower body, including multi-directional lunges, inchworms, bodyweight squats and spidermans. Upon completion, three practice trials were provided for each test where subjects were instructed to perform them at 75, 90 and 100% of their perceived maximal effort. All tests were performed in an indoor handball court, and participants wore handball shoes through all assessments. Three minutes rest were given between the last practice trial and the start of the first test.

Single leg countermovement jump (SLCMJ). The SLCMJ was conducted on a contact mat (Chronojump, Boscosystem, Barcelona Spain) measuring jump height in centimetres (cm). Subjects were required to step onto the centre of the contact mat with one leg and place their hands on their hips. When ready, subjects performed a countermovement to a self-selected depth before accelerating as forcefully as possible into a unilateral vertical jump, following the instructions to 'jump as high as you can'. The non-jumping leg was slightly flexed at the knee with the foot hovering next to the ankle of the jumping leg. No additional swinging of the non-jumping leg was allowed during the jump and hands were required to remain fixed at the hips. Any deviations from these criteria resulted in a void trial and subsequently retaken. Three trials were performed on each leg with 60-seconds rest provided between each trial. The highest jump on each leg was then used for subsequent data analysis.

Single leg lateral jump (SLLJ). The SLLJ measured lateral jump distance (in cm) with a standard measuring tape that was fixed to the floor. Subjects started just behind 0cm with a selected test leg and performed a countermovement to a self-selected depth before jumping laterally as far as possible along the direction of the tape measure (without landing directly on it) with hands placed and held on the hips throughout. Owing to the increased difficulty of this test (by virtue of jumping in the frontal plane), the landing was performed on both limbs to increase the chance of a stable landing. Subjects were required to stick the landing for 2-seconds with the distance measured from the outside edge of the landing foot (part of the foot closest to 0cm). Three trials were performed on each leg with 60-seconds rest provided between each trial. The trial with the furthest jump on each leg was then used for subsequent data analysis.

Single leg broad jump (SLBJ). The SLBJ measured horizontal jump distance (in cm) with a standard measuring tape that was fixed to the floor. Subjects started with their toes just behind 0cm with a selected test leg and performed a countermovement to a self-selected depth before jumping as far forward as possible along the direction of the tape measure (without landing directly on it) with hands placed on the hips throughout. Subjects were required to land on the same leg and stick the landing for 2-seconds with the distance measured from the heel of the landing foot. The non-jumping leg was slightly flexed at the knee with the foot hovering next to the ankle of the jumping leg. No additional swinging of the non-jumping leg was allowed during the jump. Any deviations from these criteria resulted in a void trial and subsequently retaken. Three trials were performed on each leg with 60-seconds rest provided between each trial. The furthest jump on each leg was then used for data analysis.

Change of direction speed test. This test was conducted in line with previous research by Meylan et al. (2009). Subjects were instructed to conduct two 180° changes of direction with the same leg, for a total distance of 20m. The first change of direction was performed after a distance of 7.5m, whereby the subject then sprinted 5m before the second 180° change of direction, and subsequently sprinted another 7.5m to finish the test. A trial was considered successful if the entire foot passed the marked line during the change of direction component. Total time was measured with photocell beams, placed on the starting line and 10m from it, and connected to a computer (Chronojump, Boscosystem, Barcelona, Spain). Three trials were performed turning off both the dominant and non-dominant legs with 60-seconds rest provided between each trial. The fastest trial was used for data analysis.

V-cut test. Subjects performed a 25-m sprint with four 45° changes of direction, each after a distance of 5m (Gonzalo-Skok et al., 2015). For the trial to be valid, subjects had to pass the line with each respective foot at every turn, which was clearly marked on the floor. Failure to adhere to these protocols resulted in a void trial, which was subsequently retaken after the appropriate rest period of 60-seconds. The distance between each pair of cones was 0.7m. A photocell beam sensor was connected to the Chronojump software in order to acquire data (Chronojump, BoscoSystem, Barcelona, Spain). Three trials were performed with 60-seconds rest provided between each and the fastest trial was subsequently used for further analysis.

8 x 10m repeated sprint test. This test is related to an athlete's capacity to resist fatigue during a change of direction task. The test involved eight continuous repetitions of a 10m sprint, with each 10m sprint requiring a 180° change of direction at the half way point (5m). A photocell beam sensor was connected to the Chronojump software in order to acquire data (Chronojump BoscoSystem, Barcelona, Spain). With the intention of being able to observe the association between inter-limb asymmetries and performance when athletes are in an acute state of 'fatigue', we modified this previously validated CODS test (Castillo-Rodríguez et al., 2012) by carrying out eight consecutive sprints (no rest between any of them), instead of a single maximal effort. Owing to this test acutely inducing fatigue, it was only performed twice; each time ensuring that all turns were conducted off the same limb. A rest period of five minutes between trials was provided, with the outcome of total time for all eight sprints combined and used for further analysis.

20m sprint test. Linear speed was assessed by means of a 20m sprint from a staggered 2-point start position (front foot 0.5m behind the start line). A photocell beam sensor was connected to the Chronojump software in order to acquire data (Chronojump BoscoSystem, Barcelona, Spain). Three trials were performed with 60-seconds rest provided between each and the fastest trial then used for data analysis.

Statistical Analysis

All data was initially computed as means and standard deviations (SD) in Microsoft Excel and later transferred into SPSS (version 21.0; SPSS, Inc., Armonk, NY, USA) for additional analyses when required. Absolute and relative reliability was calculated via the coefficient of variation (CV) and intraclass correlation coefficient (ICC) with absolute agreement, respectively. CV values < 10% were considered acceptable (Cormack et al., 2008) and ICC's were interpreted in line with previous suggestions from Koo and Li (2016) where values > 0.9 = excellent, 0.75-0.9 = good, 0.5-0.74 = moderate, and < 0.5 = poor.

Noting that asymmetries may favour either side depending on which limb scores larger (Bishop et al., 2018a; Lake et al., 2018), a Kappa coefficient was calculated to determine how consistently asymmetries favoured the same side during jump tests. Kappa values were interpreted in line with suggestions from Viera and Garrett (2005), where ≤ 0 = poor, 0.01-0.20 = slight, 0.21-0.40 = fair, 0.41-0.60 = moderate, 0.61-0.80 = substantial, and 0.81-0.99 = almost perfect.

A one-way repeated measures ANOVA was conducted to determine whether significant differences in asymmetry scores were present between jump tests, with statistical significance (set at $p < 0.05$) identified via Bonferroni post-hoc analysis. Pearson's r correlations were conducted to determine the relationship between asymmetry scores and performance tests, with statistical significance set at $p < 0.05$.

The following criteria were adopted for interpreting the magnitude of correlation between test measures: ≤ 0.1 = trivial; 0.1-0.3 = small; 0.3-0.5 = moderate; 0.5-0.7 = large; 0.7-0.9 = very large and 0.9-1.0 = almost perfect (Hopkins et al. 2009). Finally, inter-limb asymmetries were calculated using a percentage difference equation: 100/(max value)*(min value)*-1+100 (Bishop et al., 2018b; Bishop et al., 2018c).

Results

Mean test scores, inter-limb asymmetries and reliability statistics are presented in Table 1. All tests reported acceptable variability with CV's < 10% and good to excellent reliability with ICC's ≥ 0.89. Kappa coefficients are presented in Table 2 and show that asymmetries rarely favoured the same side between jump tests (Kappa = -0.05 to 0.15), indicating that any existing side-to-side differences during jump tests are independent of each other.

Owing to the independent nature of these asymmetries, individual jump asymmetry data are presented in Figures 1-3. Remembering that any side-to-side differences should be reported in the context of the CV, the dotted lines show when an individual's asymmetry score is greater than the test variability. When considering how many subjects showed asymmetries greater than the respective test CV score, 24 subjects (57%) reported larger values during the SLCMJ, 23 subjects (55%) showed larger values during the SLLJ, and 21 subjects (50%) showed larger values during the SLBJ test. This indicating that many subjects had asymmetries greater than the test variability score, which likely suggests real imbalances (Bishop et al., 2018b; Exell et al., 2012). Results from the one-way ANOVA showed significantly greater asymmetries in the SLCMJ compared to the SLBJ (p = 0.006).

Pearson's *r* correlations between jumping asymmetries and performance test scores are presented in Table 3. Moderate correlations were found between jump height (SLCMJ) and large correlations were found between jump distance (SLLJ) asymmetries and jump performance. In addition, moderate correlations were found between jump height (SLCMJ) asymmetries and repeated sprint performance. Further to this, moderate correlations were found between jump distance (SLLJ) asymmetries and multidirectional CODS and sprint performance. No significant correlations were shown between asymmetries and 20m sprint.

*** INSERT TABLES 1-3 ABOUT HERE ***

*** INSERT FIGURES 1-3 ABOUT HERE ***

Discussion

The aims of the present study were to determine the relationships between inter-limb asymmetries and measures of physical performance, and to quantify whether asymmetries consistently favoured the same side during three commonly used unilateral jump tests, in adolescent handball players. Results showed that jump height and distance-based asymmetries were associated with reduced performance during jumping, CODS and repeated sprint tests; but not linear speed. In addition, asymmetries rarely favoured the same side between jump tests.

Mean data for all test protocols, inclusive of test reliability and mean inter-limb asymmetry values (where appropriate), were calculated (Table 1). All tests reported good to excellent reliability (ICC range = 0.89-0.98) and acceptable variability (CV range = 1.3-8.9%), indicating that results can be interpreted with confidence. When mean asymmetry values are viewed, all jump tests reported larger between-limb differences than the CODS or repeated sprint tests, suggesting that they may be more sensitive at highlighting any existing imbalances than the outcome measure of CODS time alone. In addition, the SLCMJ showed significantly larger (p = 0.006) asymmetries than the SLBJ which is in agreement with previous research. Lockie et al. (2014) reported inter-limb differences of 10.4% for the SLCMJ, 5.4% for the SLLJ, and 3.3% for the SLBJ using 30 adult team sport athletes. Bishop et al. (2018c) reported significantly larger asymmetries for the SLCMJ (12.5%) compared to the SLBJ (6.8%) in elite youth female soccer players. As such, it would appear that the SLCMJ may be more sensitive at detecting inter-limb asymmetries than horizontal or lateral jump tests, which has been previously suggested (McCubbine et al., 2018), and is likely a useful test option for practitioners if they wish to quantify limb differences from jump tests.

The Kappa coefficient (Table 2) was calculated in order to know how frequently jumping asymmetries favor the same side among different measurements (i.e. right or left). This method of analysis was chosen because it describes the proportion of agreement between two methods after any agreement by chance has been removed (Cohen, 1960). Results show only ‘slight’ levels of agreement for the side consistency of asymmetry between jumps (-0.05 to 0.15). Previous research from Loturco et al. (2018) detected inter-limb asymmetries during isokinetic dynamometry, tensiomyography, and CMJ and squat jumps, and concluded that asymmetries from these three methods were not inter-related. This is further supported in recent research from Bishop et al. (2018a) who used the Kappa coefficient to report the side consistency of peak force asymmetries between the SLCMJ and SLBJ. The Kappa coefficient was 0.05, again indicating very low levels of agreement in terms of which side favoured the imbalance. Consequently, this provides further support for the task-specific nature of asymmetries and arguably precludes the use of a single test as the sole screening method for the prevalence of existing side-to-side differences.

Although the correlations between jumping asymmetries and physical performance (Table 3) do not show an overall negative influence on the performance of the different tested capabilities, probably because of the task-dependent nature of asymmetries, some negative correlations should be stand out. In this sense, negative correlations between jump height asymmetries and jump performance in the SLCMJ ND (*r* = -0.47) were found in the present study, and similar results have been recently showed at different ages (under-16, *r* = -0.51, -0.54; under 23, *r* = -0.52, -0.77 and under-18, *r* = -0.58, -0.40) in elite academy soccer players (Bishop et al., 2019). Related to jump distance asymmetries, no meaningful correlations were found between SLBJ and jump performance in our study, which is in agreement with previous research using this test in youth female soccer players (Bishop el al. 2018c) and youth tennis players (Madruga-Parera, et al., 2019a). Furthermore, negative correlations were found between SLLJ asymmetries and SLBJ D (*r* = -0.32) and SLLJ ND (*r* = -0.52) performance, although no correlations in the same tests were found in Madruga-Parera et al. (2019a) and Fort-Vanmeerhaeghe et al. (2015) in youth tennis players and female basketball players, respectively. Thus, it seems a relationship between larger jumping asymmetries and jump performance exists in in youth handball players, although it is not possible to establish a clear relationship. These results highlight the importance of test selection when aiming to detect between-limb differences.

Significant moderate correlations were shown for jump height asymmetries and time taken to complete the 8 x 10 repeated sprint protocol (*r* = 0.35-0.40). Noting that in this instance, a positive correlation is indicative of higher total time to complete the repeated sprint test; these results would suggest that larger asymmetries during the SLCMJ are associated with reduced repeated sprint performance. The same principle can also be said for jump distance asymmetries during the SLLJ, where significant correlations were found with the V-cut test (*r* = 0.32) and CODS test (*r* = 0.29-0.31). In contrast, no significant relationships were previously found between jumping asymmetries and CODS performance in youth tennis players (Madruga-Parera et al., 2019a) and female basketball players (Fort-Vanmeerhaeghe et al., 2015). Related to sprint capacity, no correlations with jumping asymmetries were found, as previously found in recreational team-sport athletes (Lockie et al., 2014). Furthermore, strength asymmetries have not been related to sprint performance as well (Lockie et al., 2017). These results contrast with others studies in female and male soccer players, where correlations between SLCMJ height asymmetry and reduced sprinting performance were found (Bishop et al, 2018c; Bishop et al. 2019). The disparity of this data could be explained by the importance of correctly selecting tests to determine asymmetries based on age, gender, sport and positional differences where applicable.

Therefore, in our study, both jump height and distance asymmetries would appear to be associated with reduced performance during jumping, changing direction and repeated sprint-based tests. Intuitively, explaining these findings are somewhat challenging. However, the very nature of being asymmetrical during jumping would indicate the reduced capacity of one limb relative to the other (Maloney et al. 2018). Thus, the associated force production often associated with CODS movements

(Young et al., 2001) might then be detrimentally affected if one limb cannot produce as much force, which may in part explain the association between asymmetry and CODS performance. In addition, previous research has highlighted that strength may also be a decisive factor (rather than asymmetry) when affecting physical performance. Considering our sample, comprised of youth players, it is plausible to understand the high asymmetries found in the present study, as previously happen in less trained athletes (Bazyler et al. 2014, Maloney et al. 2018). This condition could explain the low performance level in the different tests carried out.

The asymmetry scores for each individual athlete are presented in Figures 1-3 and each test shows a dotted line which indicating the CV for each test. The relevance here being that when asymmetry scores surpass the CV, the imbalance is greater than test variability and can likely be considered real (Bishop et al., 2018b; Exell et al., 2012). When determining whether individual asymmetry scores were greater than the CV, the SLCMJ showed 24 athletes surpassed test variability, 23 for the SLLJ and 21 for the SLBJ. Therefore, it is evident that > 50% of these athletes are exhibiting real side-to-side differences during multi-directional jump testing. Furthermore, when viewing the asymmetry axis on each graph, it is apparent that the scale is much greater on the SLCMJ and SLLJ compared to the SLBJ. Thus, vertical and lateral jump testing may potentially detect larger inter-limb differences than horizontal jump tests. This is supported by Lockie et al. (2014) who reported asymmetry values of 10.4 and 5.1% for the SLCMJ and SLLJ, compared to 3.3% for the SLBJ. Therefore, if asymmetry profiling is needed for team sport athletes, multi-directional jumping seems ecologically valid, and practitioners may find the vertical and lateral jumping are most effective when detecting existing between-limb differences.

Practical Applications

In conclusion, multi-directional jumping asymmetries appear to be independent of each other. Moreover, these asymmetries are detrimental to jumping, CODS and repeated sprint performance, but not linear speed. Given the negative association of jumping asymmetries and the reduction of performance tests, it is suggested to apply training interventions with the intention to reduce inter-limb asymmetries. Previous research has highlighted unilateral training such as rear foot elevated split squats and unilateral CMJ as effective methods to reduce imbalances (Gonzalo-Skok et al., 2017), as well as unilateral coordinative training with an iso-inertial device (Gonzalo-Skok et al., 2019). These suggestions could be useful when programming for youth handball players given the prevalence of unilateral movement patterns in the sport.

Conflicts of Interest Statement

The authors report no conflicts of interest with this study.

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TABLES AND FIGURES
STUDY 2

Table 1. Mean data for jump testing, inter-limb asymmetries and reliability statistics.

Fitness Test	Mean ± SD	Asymmetry %	CV (%)	ICC (95% CI)
SLCMJ-D (cm)	15.7 ± 3.6	11.2 ± 8.4*	8.9	0.96 (0.93-0.98)
SLCMJ-ND (cm)	13.9 ± 3.6		7.7	0.95 (0.92-0.97)
SLLJ-D (cm)	140.7 ± 20.5	8.3 ± 7.5	5.5	0.95 (0.91-0.97)
SLLJ-ND (cm)	129.2 ± 21.5		5.8	0.96 (0.92-0.98)
SLBJ-D (cm)	143.2 ± 25.3	6.4 ± 4.6	6.1	0.92 (0.86-0.95)
SLBJ-ND (cm)	134.0 ± 24.3		6.5	0.94 (0.88-0.97)
CODS-D (s)	5.3 ± 0.5	2.6 ± 2.3	1.9	0.96 (0.93-0.98)
CODS-ND (s)	5.4 ± 0.5		2.2	0.96 (0.93-0.98)
8x10-D (s)	14.9 ± 2.0	5.8 ± 5.7	4.4[a]	0.89 (0.79-0.94)[a]
8x10-ND (s)	15.8 ± 2.2			
V-cut (s)	7.3 ± 0.6	-	1.6	0.97 (0.95-0.99)
20m (s)	3.1 ± 0.3	-	1.3	0.98 (0.97-0.99)

* significantly different from SLBJ % ($p = 0.006$)

[a] pooled data from both limbs, noting that only 1 trial was performed with turns off each limb (due to it being a repeated sprint test)

CV = coefficient of variation; ICC = intraclass correlation coefficient; CI = confidence intervals; D = dominant; ND = non-dominant; SLCMJ = single leg countermovement jump; SLLJ = single leg lateral jump; SLBJ = single leg broad jump; CODS = change of direction speed; s = seconds

Table 2. Kappa coefficients comparing asymmetry side consistency between jump height and distance in the single leg countermovement, lateral, and broad jump tests.

Test Comparison	Kappa Coefficient	Descriptor
SLCMJ – SLLJ	0.15	Slight
SLCMJ – SLBJ	-0.05	Poor
SLBJ – SLLJ	0.00	Poor

SLCMJ = single leg countermovement jump; SLLJ = single leg lateral jump; SLBJ = single leg broad jump

Table 3. Pearson's *r* correlations between asymmetry scores and physical performance tests.

Asym %	SLCMJ D	SLCMJ ND	SLLJ D	SLLJ ND	SLBJ D	SLBJ ND	20m	V-cut	CODS D	CODS ND	8x10 D	8x10 ND
SLCMJ	-0.13	-0.47**	-0.06	-0.09	-0.24	-0.26	0.18	0.07	0.09	0.11	0.40**	0.35*
SLLJ	-0.04	-0.06	-0.06	-0.52**	-0.32*	-0.30	0.13	0.32*	0.31*	0.29	0.01	0.03
SLBJ	-0.19	-0.20	-0.05	-0.02	-0.03	-0.25	0.11	< 0.01	0.03	-0.01	0.20	0.30

** significant at $p < 0.01$; * significant at $p < 0.05$

Asym = asymmetry; SLCMJ = single leg countermovement jump; SLLJ = single leg lateral jump; SLBJ = single leg broad jump; D = dominant; ND = non-dominant; CODS = change of direction speed

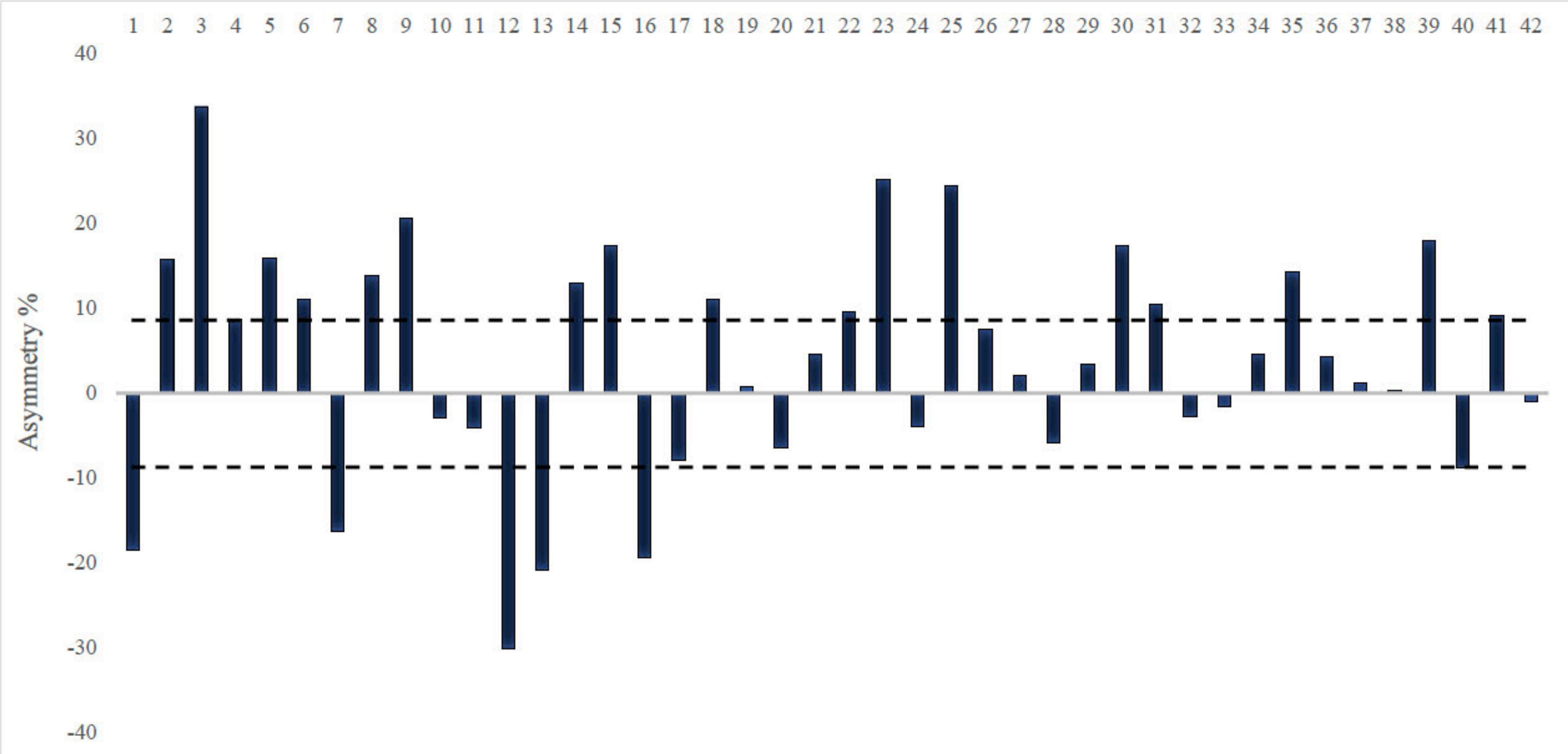

Figure 1. Individual single leg countermovement jump (SLCMJ) asymmetry scores ($n = 42$). N.B1: above 0 indicates that asymmetry is favoured on the right leg and below 0 indicates asymmetry favours the left leg. N.B2: dotted line indicates the average CV value for SLCMJ test (8.27%).

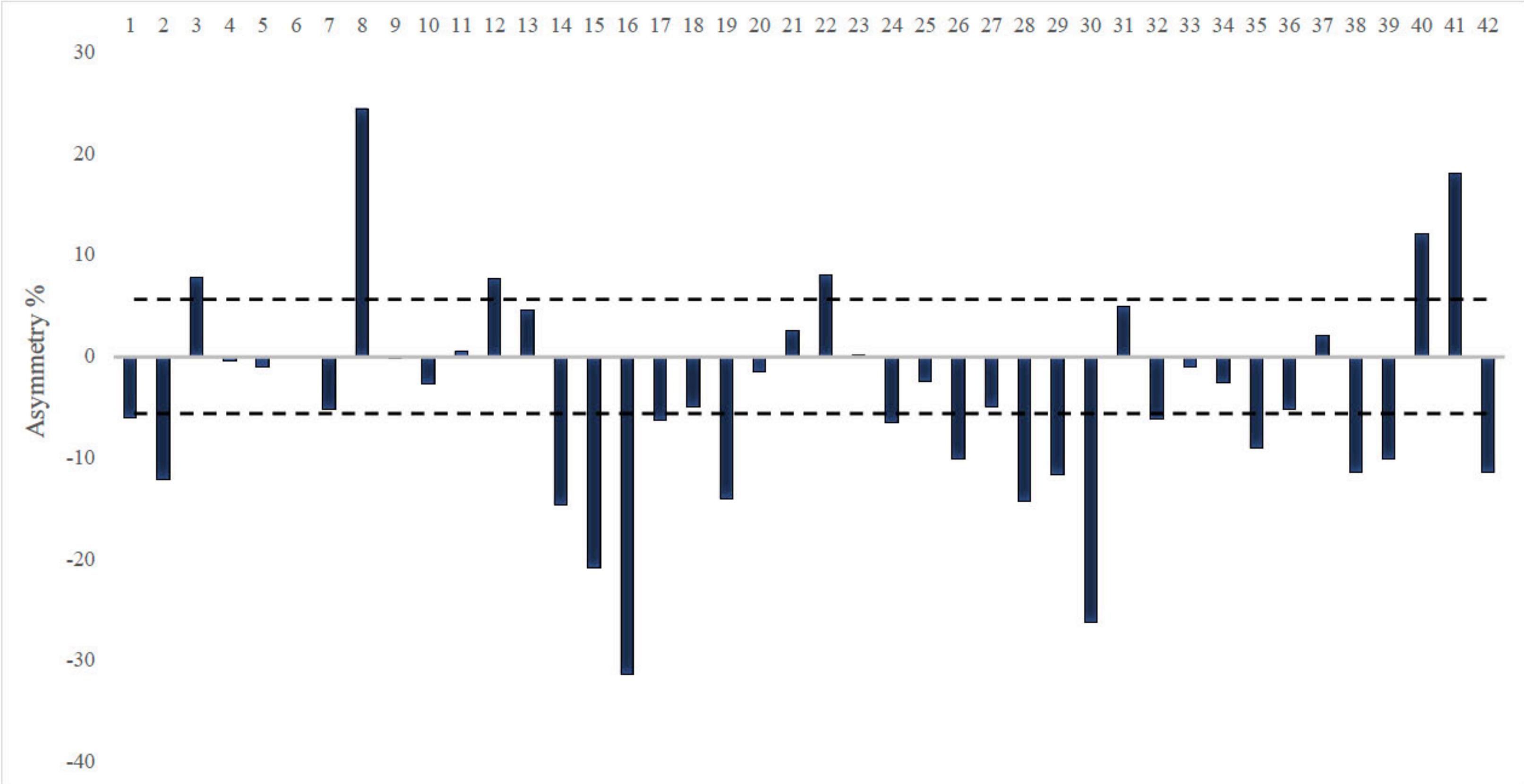

Figure 2. Individual single leg lateral jump (SLLJ) asymmetry scores (n = 42). N.B1: above 0 indicates that asymmetry is favoured on the right leg and below 0 indicates asymmetry favours the left leg. N.B2: dotted line indicates the average CV value for SLLJ test (5.65%).

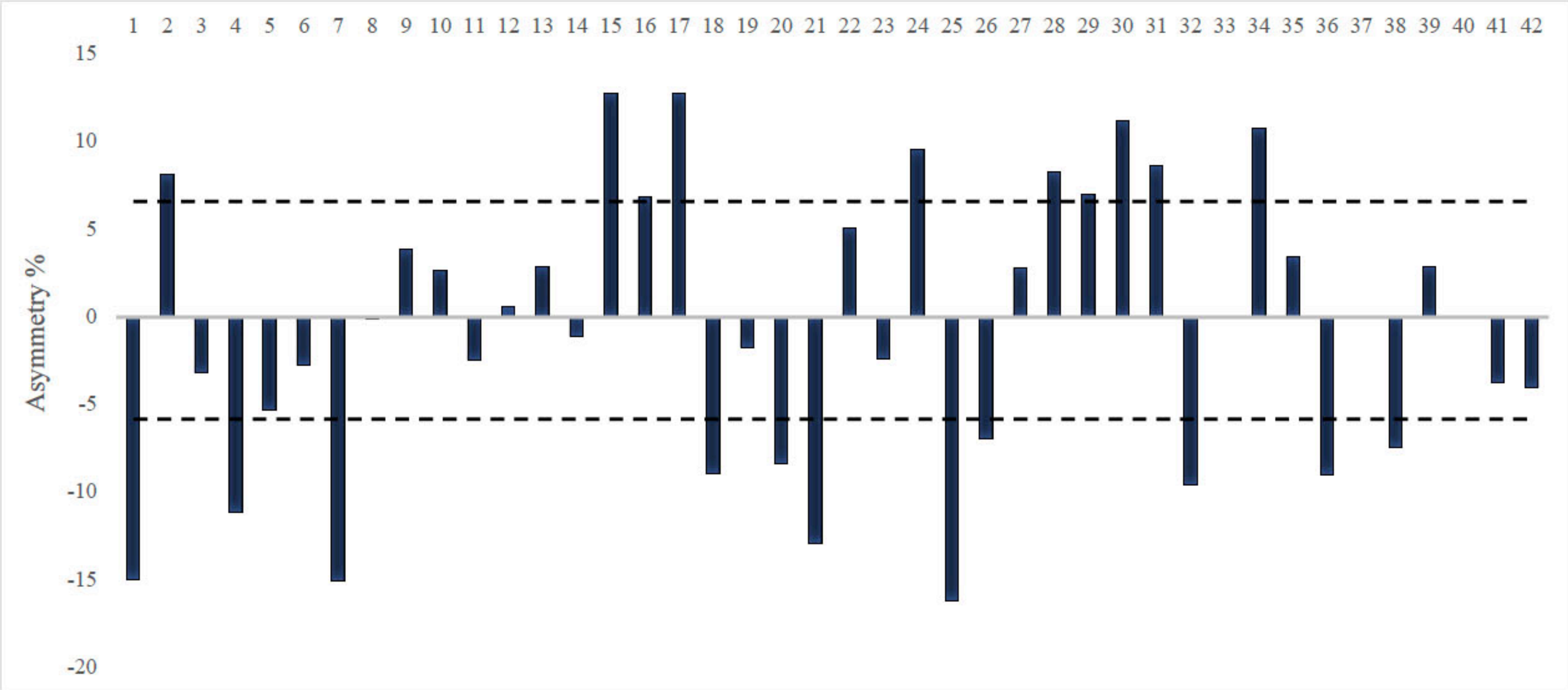

Figure 3. Individual single leg broad jump (SLBJ) asymmetry scores (n = 42). N.B1: above 0 indicates that asymmetry is favoured on the right leg and below 0 indicates asymmetry favours the left leg. N.B2: dotted line indicates the average CV value for SLBJ test (6.28%).

STUDY 3

Interlimb Asymmetries in Youth Tennis Players: Relationships with Performance

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Abstract study 3

Change of direction speed (CODS) has been highlighted as a critical component of tennis. Inter-limb asymmetries have been commonly studied in jump tests, but less attention given to the topic during CODS. The aim of this study was to quantify inter-limb asymmetries in jumping and CODS (during traditional and isoinertial tests) and establish their relationship with measures of physical performance. Twenty-two elite youth tennis players (16.3±1.4 years) performed single leg countermovement jump (SLCMJ), broad jump (SLBJ) and lateral jump (SLLJ), a double 180° turn CODS test, and shuffle lateral step and crossover step with an iso-inertial resistance device. Paired samples *t*-tests revealed significant differences between limbs for all tests ($p < 0.05$). Inter-limb asymmetry scores ranged from 1.83-15.03% and a one-way repeated measures ANOVA showed significant differences between inter-limb asymmetry scores across multiple tests ($p < 0.05$). Spearman's rank order *r* correlations showed significant negative relationships between CODS asymmetry and SLCMJ performance on both limbs ($r = -0.50$; $p = 0.02$ and $r = -0.53$; $p = 0.01$) and CODS performance on both limbs ($r = 0.50$; $p = 0.02$ and $r = 0.63$; $p = 0.002$). These results show the test-specific nature of asymmetries in youth tennis athletes, with the SLCMJ presenting the greatest magnitude of asymmetry. Furthermore, inter-limb differences during CODS were associated with reduced performance during jumping and CODS tests, suggesting the monitoring of asymmetries within this population may therefore be warranted.

Key Words: Change of direction speed; jumping; symmetry; youth athletes

INTRODUCTION

Tennis is a multi-directional sport characterized by numerous unilateral movement patterns with repeated high intensity efforts, often lasting 5-10 seconds with 10-20 seconds of recovery (14). Such high intensity actions include; sprints, accelerations, decelerations, changes of direction and jumps (14). Owing to the court dimensions (11.90 x 10.97 m), tennis players can run on average about 4 m (maximum of between 8 to 12 m) (42), meaning accelerations and decelerations are of primary importance in tennis in comparison to top speed (14,27). In addition, change of direction speed (CODS) has been highlighted as a critical component of tennis performance (13), and it has been suggested that up to 70% of movements on court can be accounted for during lateral movements (27). Finally, vertical power has also been suggested to be an important aspect due to the application of explosive force during the tennis serve in professional players (18). Consequently, the concurrent development of multiple physical qualities to improve these interconnected skills are key factors to optimize tennis performance, and this has been reflected by the reported relationships between vertical power and speed in youth tennis players (17,38).

The concept of inter-limb asymmetries refers to the difference in function or performance between limbs (1,2,25). Literature to date has highlighted inconsistent findings when assessing the association between side-to-side differences in jump tests and measures of physical performance (3). For example, recent literature by Bishop et al. (2) highlighted that jump height asymmetries ~12.5% during the single leg countermovement jump (SLCMJ), were associated with reduced acceleration (r = 0.49 to 0.59) and jumping ability

(r = -0.47 to -0.58) in youth female soccer players. Maloney et al. (31) reported that jump height asymmetries (from a unilateral drop jump) were associated with slower CODS times (r = 0.60) involving multiple 90° cuts. In contrast, Dos'Santos et al. (10) showed no relationships between single and triple hop for distance asymmetries when compared to two CODS tasks. Lockie et al. (30) also reported no association between asymmetries from SLCMJ, broad jump, and lateral jump tests, and speed or CODS tasks. Thus, when assessing inter-limb differences from jumping tests, the association with athletic performance is still unclear and further research in this area is warranted.

Where tennis concerned, asymmetry literature to date is scarce, which is arguably somewhat surprising given the commonality of unilateral actions and reactive nature of the sport (12). In fact, Sanchis-Moysi et al. (39) showed that the non-dominant iliopsoas muscle was 13% larger than the dominant one in professional tennis players, with professional soccer players also showing a similar trend in results. In contrast, Rynkiewicz et al. (36) showed no significant differences in asymmetries in lower limb muscle mass in youth tennis players. Related to more functional tasks, Sannicandro et al. (40) reported the presence of inter-limb asymmetries during jump and CODS tests, and showed that an integrated neuromuscular training programme (consisting of balance, strength and jumping exercises) was effective at reducing asymmetries in youth tennis players. However, it is worth mentioning that the reduction of asymmetries did not result in faster speed or CODS times.

Recent literature has also aimed to quantify asymmetries in CODS tasks themselves. It should be noted that the relationships between asymmetry in

CODS have been shown by Maloney et al. (31) although relationships with a negative effect on performance could not be established. Dos'Santos et al. (10) investigated inter-limb differences during a modified 505 and 90° cut test in collegiate team sport athletes. Differences between limbs were 2.3 and 4.3% respectively, highlighting relatively small side-to-side asymmetries. In a separate study, Dos'Santos et al. (11) reported average asymmetries of 2.3% from the 505 test, again highlighting the small differences between limbs. This may be explained by the relatively short time frame it takes to complete a CODS test. This is also supported from Dos'Santos et al. (11), who noted that when the actual change of direction component is isolated by virtue of the change of direction deficit, asymmetries increased substantially to ~12%. Thus, athletes may be able to mask inter-limb differences during CODS tests, if only the total time is used as an outcome measure (33). Consequently, this justifies the need to assess asymmetries during CODS tasks by isolating the change of direction measure action itself, when detecting side-to-side imbalances.

While asymmetry assessments for jump and CODS tests are common and useful, the calculation of existing strength or muscle power differences is rare as a method of field-based testing. Hart et al. (20) used the unilateral isometric squat to detect inter-limb differences in Australian rules football players and compared results to kicking accuracy. Inaccurate kickers showed peak force asymmetries of 8%, compared to the accurate group who were almost perfectly symmetrical (-1%). More recently, iso-inertial resistance has gained popularity as a method for training athletes (19,41). This training involves additional eccentric overload, which is advantageous for athletes given the previously reported importance of eccentric strength and measures of physical performance (23,41). However, to the authors' knowledge, no study to date has used an eccentric overload assessment to detect inter-limb asymmetries in strength. Given the importance of strength as a pre-requisite to enhance power, speed and CODS (19), the detection of existing strength imbalances seems warranted in tennis athletes, due to the high volume of unilateral actions performed in the sport (14,27).

The primary aim of this study was to quantify inter-limb asymmetries in jumping, CODS and muscle power tests from a fitness testing battery associated with tennis performance. A secondary aim was to establish the relationships between the reported inter-limb asymmetries and performance during the fitness testing battery. It was hypothesised that: 1) power output in change of direction from the iso-inertial device would detect larger asymmetries than total time from CODS; 2) larger asymmetries would be associated with impaired performance.

METHODS

Experimental approach to the problem

The current study aimed to assess the unilateral neuromuscular performance in youth tennis players across six separate tests. These tests measured unilateral jumps, in the vertical, horizontal and lateral directions, CODS and muscle power output in specific change of direction actions (lateral shuffle step and crossover step) which were tested with conical pulley (iso-inertial device). Multiple studies have suggested jump and CODS tests for the quantification of side-to-side differences (2,4,11,28). Relationships were assessed between asymmetry values and performance test scores, enabling a greater understanding of the associations between imbalances and jumping and CODS performance in youth tennis athletes.

Subjects

Twenty-two tennis elite players were included in this study (10 boys and 12 girls; age: 16.3 ± 1.4 years; height: 1.73 ± 0.1 m; body mass: 62.6 ± 9.7 kg; 18 right lower limb dominance, 4 left lower limb dominance). Tennis players were tested in the competitive period. Subjects were eligible for inclusion if they had 8 years of competitive tennis experience. Subjects were excluded if they presented any injury (overuse or acute) at the time of testing. All subjects were actively participating in a professional development program at the time of the experiment, performing 6 sessions per week, lasting approximately 150 minutes per session (including on court and fitness works, as well as recovery periods). Tennis players were also subjected to non-regular calendar tournaments, as is typical in tennis. Written informed consent was obtained from both subjects and their parents, owing to the age of subjects. This study was approved by the [** DELETED FOR PEER REVIEW **] ethics committee.

Procedures

Subjects arrived at the sports academy prior to the first training session of the week having been instructed not to eat for the preceding 2 hours and avoid caffeine consumption for at least 24 hours before the tests. All athletes were previously familiarized with the testing procedures due to their regular physical assessments throughout the tennis season. Subjects were tested in two separate days, each separated by 72 hours. During the assessment, the current training load was reduced to 50%. Day one consisted of three unilateral jump tests and the CODS test. On day two, the players performed the specific change of direction actions with the iso-inertial device. The iso-inertial tests were performed on the second day, owing to the likelihood of it impacting the performance of other tests if conducted on the same day. Each subject went through a specific warm up procedure consisting of five minutes of light jogging, dynamic stretches and strength work for the lower body (such as multi-directional lunges, inchworms, bodyweight squats, and planks). Upon completion, three practice trials were provided for each test where subjects were instructed to perform them at 75, 90 and 100% of their perceived maximal effort. Three minutes rest was given between the last practice trial and the start of the first test. For the change of direction test with iso-inertial resistance, an incremental procedure was performed (37). Each set consisted of performing two initial reps up to build up momentum, owing to the additional eccentric load that accompanies this method. Subsequently, maximal repetitions were asked to achieve maximal muscle power and complete the set. The set was stopped after doing two consecutive reps under the maximal registered value. Each trial was separated by a 4-minute recovery period. Data of the maximum power in concentric and eccentric phases were registered for each iso-inertial test.

Change of Direction Speed (CODS) test

Subjects performed two changes of direction of a 180° turn with the same leg in each trial (Figure 1). The first change of direction was done after 7.5 m from the beginning of the test, with the second change of direction performed after 5 m in respect to the first change of direction. The subjects sprinted for a total distance of 20 m. Time in the CODS test was measured with photocell beams (Chronojump Boscosystem, Barcelona, Spain) (7), placed on the starting line and 10 m away. The fastest time of the three trials for each leg was used for analysis. A trial was considered successful if the entire foot passed all lines while changing direction. Each trial was separated by a 60 second recovery period.

** PLEASE INSERT FIGURE 1 ABOUT HERE **

Single leg jumps tests

Subjects performed three single leg countermovement jumps: vertical jump (SLCMJ), single leg broad jump (SLBJ) and single leg lateral jump (SLLJ) in a randomized order. They were instructed to stand on one leg, and flex at the hip and knee to a self-selected depth, and then jump as high or as far as possible in the ensuing concentric phase, landing on two feet for each task (vertical, horizontal, or lateral). Three successful trials per limb were collected. Each trial was separated by a 60 second recovery period. Specifically, for the SLCMJ test, the height in centimeters was calculated by a contact mat system (Chronojump Boscosystem, Barcelona, Spain) (7), with the subject starting with the foot of the selected leg on the contact mat. For SLBJ and SLLJ (i.e., left leg = jumping to the right side) tests, the subject stood with the selected leg just behind a marked line on the ground. The distances were calculated in centimeters with a tape measure. The achieved longest distance to the nearest 0.01 m was used for analysis.

Change of direction with iso-inertial resistance

Subjects stood beside a conical pulley (CP), an iso-inertial device (Byomedic System SCP, Barcelona, Spain) of a metal flywheel (diameter: 0.42 m) with up to 16 masses (0.421 kg and 0.057 m diameter each one). A fixed axis is located at the center of the beam around which the masses rotate. The moments of inertia were 0.12 kg_m2 and 0.27 kg_m2 for 4 and 16 masses respectively. The modification of the moment of inertia is made by adding any number of the 16 masses on the edge of the flywheel and also by selecting four positions (P1, P2, P3 or P4), changing the location of the pulley that is closest to the cone (32).

The maximum power test was recorded by SmartCoach Power Encoder (SmartCoach Europe AB, Stockholm, Sweden), with associated SmartCoach software (v3.1.3.0). Subjects were familiar with the device and the type of tasks, since it is part of their regular strength training protocols. Subjects were instructed to perform an incremental test to register the maximum power score, set to the maximum point of the power curve. Every set with a different load was stopped by two possibilities: either by completing eight repetitions or by a decrease of 10% of the maximum value of the set. The test started with 10 masses, and 2 masses were added in every set if the power of the previous one was exceeded, until all 16 masses had been completed. For the present sample, only P1 was necessary to achieve the maximum power. The performed actions were shuffle lateral step (SHL) (Figure 2A), and crossover step (CRO) (Figure 2B).

Concentric (C) action is identified by the acceleration phase, while the eccentric (E) one is related to the deceleration phase, with both phases analyzed separately in the present study.

The attempt was considered valid if the subject was located 1 m from the conical pulley and performed the task with maximum effort. Verbal encouragement was provided throughout to ensure maximal effort was given during testing. In the SHL the subject was instructed to perform a lateral lunge in the frontal plane. The movement began with the feet aligned in this plane and the leg closer to the CP flexed to approximately 100-120° at the hip and knee. Repeated shuffle lateral steps of maximum intensity followed, without allowing any external hip rotation. For the CRO test, the movement began with the feet aligned in the frontal plane and the leg closer to the CP flexed to approximately 100-120° at the hip and knee. The action of the CRO was performed at maximum intensity, pivoting on the farthest foot from the CP by a rotation of the whole body. While doing this action, the nearest leg (regarding to the CP) advanced over the pivoting foot in the sagittal plane, ensuring the hips and shoulders remained at the same height during the step. At the end of this acceleration phase, the subject returned to the starting position with the feet aligned in the frontal plane.

** PLEASE INSERT FIGURE 2 ABOUT HERE **

Statistical Analysis

All data in the present study were initially recorded as means and standard deviations in Microsoft Excel and then later transferred to IBM SPSS Statistics for Windows version 22.0 (Armonk, NY: IBM Corp) for further analysis. The Shapiro-Wilk test was used to determine whether data were normally distributed. Data not following a normal distribution were root square-transformed before further analysis. Test reliability was computed via the coefficient of variation (CV), a two-way random intraclass correlation coefficient (ICC) with absolute agreement and 95% confidence intervals (CI), and typical error of the measurement (TEM). For interpretation, acceptable coefficient of variation (CV) values were considered ≤ 10% (9) and intraclass correlation coefficient (ICC) were interpreted in line with suggestions from Koo et al. (26), where values > 0.9 = excellent, 0.75-0.9 = good, 0.5-0.75 = moderate and < 0.5 = poor.

Paired sample *t*-tests were used to examine performance differences between limbs. Effect size (Cohen's *d*) calculations were performed on pairwise comparisons which were computed as the mean difference divided by the pooled standard deviation and defined as: small (< 0.2), moderate (0.2-0.5), and large (> 0.8) mean differences (8). The lower and upper limits for 95% CI were presented for the sample mean difference of each task when a significant pairwise comparison was detected.

A one-way analysis of variance (ANOVA) with repeated measures was performed to assess differences in neuromuscular asymmetries between performance tests and Bonferroni post hoc test was used to aid interpretation of the results. Partial Eta squared (η^2p) scores were calculated as measures of effect size for the ANOVA, where < 0.01 = trivial; 0.01 to 0.06 = small; 0.06 to 0.14 = medium, and > 0.14 = large (15).

Spearman's rank correlations (r) were computed to assess the relationship between the asymmetry scores of each task and performance on all tests. The following criteria were adopted for interpreting the magnitude of correlation between test measures: trivial ≤ 0.1; small = 0.1-0.3; moderate = 0.3-0.5; large = 0.5-0.7; very large = 0.7-0.9; and almost perfect = 0.9-1.0 (22). The level of significance was set to $p < 0.05$. Asymmetries were calculated for all tasks defining the dominant (D) (the limb with the better score) and non-dominant (ND) limb, using the following formula: Asymmetry index = (D – ND)/D x 100 (24). To extend the analysis of inter-limb asymmetries, individual asymmetry data was reported and the CV was used as a threshold to determine whether an asymmetry was "real" or within the error of the test, as per previous suggestions (12).

RESULTS

Table 1 shows neuromuscular performance of the D and ND limbs, the percentage of asymmetry for each task and test reliability values. Excellent test reliability was found for the SLCMJ, SLBJ and SLLJ tests (ICC ≥ 0.9) and good reliability for the CODS tests (ICC ≥ 0.7 < 0.8). COD with iso-inertial resistance also showed good reliability (Table 2). Significant differences between D and ND limbs were found across all the tasks ($p < 0.001$). The mean unilateral asymmetries ranged between 15.03% (SLCMJ) to 1.83% (CODS test).

The repeated measures ANOVA with Greenhouse-Geisser correction determined that significant differences between asymmetries in each test were present ($F_{1,28} = 63.99$, $p < 0.001$; $\eta^2p = 0.75$). The post-hoc test revealed that

SLCMJ test asymmetry was significantly higher from all the other asymmetry scores ($p < 0.05$), while CODS test showed lower significant asymmetry among all the tests carried out ($p < 0.05$), except for the case of SLBJ. Related to SLBJ test, a significant difference was found when comparing it to the concentric action of the CRO iso-inertial test ($p < 0.05$). Asymmetry percentages comparisons showed no significant differences between SHL and CRO iso-inertial tests neither for concentric nor for eccentric actions ($p > 0.05$). Owing to the variable nature of asymmetry, individual data has also been included for reported differences during jump tests (Figures 3-5).

** PLEASE INSERT TABLE 1-2 ABOUT HERE **

** PLEASE INSERT FIGURES 3-5 ABOUT HERE **

Table 3 shows the Spearman's rank correlations between asymmetry percentages and unilateral jump performance on D and ND limbs. The CODS asymmetry measure was correlated with SLCMJ performance of the D and ND limbs ($r = -0.50$, $p = 0.02$ and $r = -0.53$, $p = 0.01$ respectively), whereas all other asymmetry measures showed no significant correlations with performance tests.

** PLEASE INSERT TABLE 3 ABOUT HERE **

Table 4 shows the Spearman's rank correlations between asymmetry percentages and change of direction performance on D and ND limbs. The CODS asymmetry measure was correlated with CODS performance of the D and

ND limbs (r = 0.50, p = 0.02 and r = 0.63, p = 0.002 respectively). All other asymmetry measures showed no significant correlations with performance tests.

** PLEASE INSERT TABLE 4 ABOUT HERE **

DISCUSSION

The aim of the present study was to quantify inter-limb asymmetries across a variety of unilateral jump and CODS assessments in elite youth tennis players and to analyse the relationships between asymmetries and physical performance tests. Results showed varying magnitudes of asymmetry across tests, the largest of which was during the SLCMJ. Iso-inertial tests, biomechanically simulating a change of direction, showed larger asymmetries when comparing to the CODS test. Finally, larger asymmetry during the CODS test was associated with reduced performance during the SLCMJ and CODS tests on both limbs.

The large range of asymmetries found in the present study reflects the necessity to introduce different tests in order to provide a holistic picture of asymmetries in athletes, as has been previously suggested (2). SLCMJ showed the largest asymmetries among the different jumping tests (15.03 ± 6.91%), as has been demonstrated in previous studies using team sport athletes (10.40 ± 10.80%) (30), female basketball players (14.11 ± 8.6%) (16) and youth female soccer players (12.54 ± 10.8%) (2). Broad and lateral jump asymmetries (4.14 ± 3.72% and 6.63 ± 5.30% respectively) also showed similar magnitudes to previous studies (3.3 ± 3.0%) (30), (5.1 ± 3.9%) (16). Despite the similarity in magnitude of asymmetry to previous research, there were no associations between jump asymmetry and jump or CODS performance in the present study. This is actually in contrast to recent literature (4,5) and highlights that despite the SLCMJ showing a mean difference of 15%, the magnitude is more than likely irrelevant when assessing associations with athletic performance.

The CODS test showed a low magnitude of asymmetry (1.83 ± 1.50) in comparison to the jump tests, which is in agreement with previous research (11,16,31). It is important to underline the importance of linear speed during these tests, which could mask the existing asymmetry during a CODS task. The fact that there is a strong linear speed component, it is plausible that the outcome of total time during CODS tests is not very sensitive at detecting existing inter-limb differences. For this reason, and with the aim of isolating the change of direction action, two additional tests with iso-inertial resistance simulating the side step (SHL test) and cutting (CRO test) were used for asymmetry analysis. As hypothesized, both iso-inertial tests showed greater asymmetries in strength (7.35 ± 5.72% and 9.82 ± 9.65% for the concentric and eccentric phases of SHL; 9.31 ± 6.96% and 11.18 ± 9.01% for the concentric and eccentric phases of CRO test). Without a more mechanistic approach to analysis, it is challenging to fully explain why this might be the case; however, it is possible these greater inter-limb differences were a result of isolating the change of direction action. Given the larger differences reported, it is possible this theory has merit. This method of testing has been applied in numerous studies (19,23,35), focusing on injury prevention and performance. To our knowledge, this is the first study to determine the neuromuscular inter-limb asymmetries in actions related to changing direction with an iso-inertial resistance device. It could be recommended to introduce both functional and resistance tests in order to provide a more detailed picture of asymmetry during the change of direction action. However, it should also be acknowledged that this mode of testing showed slightly greater variability compared to jump tests. Thus, it is critical that athletes are familiar with test protocols if asymmetry is to be analyzed.

Significant negative correlations were found between CODS asymmetries and the SLCMJ on the D (r = -0.53), and ND (r = -0.57), which signifies reduced performance in the vertical jump action when asymmetries are larger in the CODS test (Table 3). Given that this study did not undertake any mechanistic investigation, it is challenging to explain these relationships. Furthermore, given that jumping and CODS are two independent actions, it is difficult to understand why imbalances during a CODS test would result in reduced jump height. Finally, given recent literature has highlighted the importance of analyzing asymmetries at an individual level (6), these correlations could be seen as occurring by chance.

An important finding related to the correlation results was the reduced performance in CODS test, in both the D and ND legs, when larger asymmetries in the same test were found (Table 4). Related to our results, Dos'Santos et al. (11) suggested that CODS asymmetries could impair 180º CODS performance in female youth netball players. Moreover, Maloney et al. (31), with recreationally active subjects, described correlations between the performance in 90º CODS test and jumping asymmetry (drop jump), showing how the faster group presented lower jump height asymmetry. However, associations with CODS (r = 0.6) were only present for the whole sample (n = 18) and there were no significant associations between CODS asymmetry and CODS performance. In the present study, the CODS test was performed with 180° turns, which could be more related to the crossover step actions frequently required by tennis players. Thus, our recommendation would be to decrease CODS asymmetry in order to potentially improve CODS performance.

Although we hypothesized to find correlations between asymmetries and performance scores in the CODS test, significant relationships were not apparent. Similar results were also expected between iso-inertial asymmetry and CODS tests, but again, were not present. Considering these results, it is possible that the iso-inertial tests, without the running phases of decelerating and accelerating (as per CODS tasks), represents a different nature of the skill measured, which may explain this lack of correlation. However, considering the importance of both lateral movements and crossover steps for tennis athletes, further research on the detection, direction and magnitude of asymmetry using these test methods seems warranted.

Despite the usefulness of these findings, this study presents some limitations. Firstly, we have not considered gender differences owing to the sample size. Future studies should aim to consider such differences. Secondly, maturation stages have not been considered in this study. Given the associated alterations in motor control (29,34), future analysis in youth athletes should aim to include this in the analysis. Thirdly, authors had no previous references related to the study of asymmetries with iso-inertial technology, and this kind of test should be considered for future studies in order to analyze muscle power asymmetries in resisted functional actions.

Practical Applications

This study offers the possibility to apply a fitness test battery for youth tennis players in order to identify existing lower limb asymmetries. From this battery of tests, there was a varying magnitude of asymmetry present, further highlighting the task-specific nature of inter-limb asymmetry. In addition, it is important to highlight the use of iso-inertial tests as a new tool to evaluate asymmetries. Given the larger magnitude of asymmetry shown when using the iso-inertial device (in comparison to total time during the CODS tests), this represents a viable means of detecting existing imbalances. However (and as per previous suggestions), longitudinal monitoring is likely required to determine how consistent the magnitude of asymmetry is over more than a single test session. Furthermore, due to some associations with reduced physical performance, it is suggested that training programs should consider the reduction of inter-limb asymmetry in youth tennis populations.

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TABLES AND FIGURES STUDY 3

Table 1: Inter-limb neuromuscular test performance, asymmetry and test reliability data.

Performance Test	Mean ± SD	Mean difference (95% CI)	ES	Asymmetry (%)	CV(%)	ICC (95%CI)
SLCMJ (cm) D	14.66 ± 3.48*	2.22 (1.71 to 2.73)	0.68	$15.03 \pm 6.91^{\#}$	3.10	0.98 (0.96-0.99)
SLCMJ (cm) ND	12.43 ± 3.06				4.11	0.97 (0.95-0.99)
SLBJ (cm) D	160.83 ± 25.84*	6.90 (3.85 to 9.96)	0.28	$4.14 \pm 3.72^{\#\#}$	1.30	0.99 (0.98-0.99)
SLBJ (cm) ND	153.92 ± 23.38				0.96	0.99 (0.98-0.99)
SLLJ (cm) D	150.16 ± 22.98*	10.07 (6.37 to 13.77)	0.45	6.63 ± 5.30	1.90	0.98 (0.97-0.99)
SLLJ (cm) ND	140.09 ± 21.99				1.84	0.98 (0.96-0.99)
CODs (sec) D	5.19 ± 0.22*	0.10 (0.06 to 0.13)	0.41	$1.83 \pm 1.43^{\#\#\#}$	1.74	0.84 (0.65-0.93)
CODs (sec) ND	5.29 ± 0.27				2.25	0.79 (0.57-0.91)
SHL /C (W) D	1296.31 ± 299.06*	97.21 (62.30 to 132.12)	0.33	7.35 ± 5.72	-	-
SHL /C (W) ND	1199.10 ± 286.38					
SHL /E (W) D	1516.20 ± 369.94*	147.40 (88.88 to 205.92)	0.40	9.82 ± 9.65	-	-
SHL /E (W) ND	1368.76 ± 366.90					
CRO /C (W) D	1608.26 ± 501.21*	159.92 (90.61 to 229.23)	0.34	9.31 ± 6.96	-	-
CRO /C (W) ND	1448.35 ± 438.77					
CRO /E (W) D	1489.73 ± 435.68*	178.80 (102.09 to 255.51)	0.45	11.18 ± 9.01	-	-
CRO /E (W) ND	1310.93 ± 355.93					

Data are presented as mean ± standard deviation. CI: confidence intervals; ES: Cohens' *d* effect size; CV: Coefficient of variation; ICC: Intraclass correlation coefficient; CI: Confidence intervals; cm: centimetres; w: wats; sec: seconds.

CODS: Change of direction speed; SLCMJ: Single leg countermovement jump; SLBJ: Single leg broad jump; SLLJ: Single leg lateral jump; SHL: Shuffle lateral step with iso-inertial device; CRO: Crossover with iso-inertial device; C: Concentric; E: Eccentric. SK: Dominant leg; ND: Non-dominant leg.

*It shows significant differences between dominant and non-dominant legs.

[#] It indicates: significantly different from all the other asymmetry scores.

[##] It indicates: significantly different from CRO/C.

[###] It indicates: significantly different from all the other asymmetry scores but not SLBJ.

Significance level $p < 0.05$

Table 2: Measures of reliability with iso-inertial resistance

	Test	Trial 1	Trial 2	TEM (95% CI)	CV (95% CI)	ICC (95% CI)
SHL	*PP L CON*	1403.4 (309.4)	1467 (451.8)	106.9 (85.7; 143.8)	18.8 (14.8; 26.1)	0.70 (0.43; 0.83)
	PP L ECC	1486.0 (312.2)	1558.8 (444.2)	127.3 (102.3; 171.3)	18.7 (14.8; 26.0)	0.72 (0.49; 0.85)
	PP R CON	1408.2 (264.6)	1460 (334.4)	87.3 (70.0; 117.5)	12.7 (10.1; 17.5)	0.70 (0.43; 0.83)
	PP R ECC	1526.4 (337.8)	1531 (394.2)	77.1 (61.8; 103.8)	10.4 (8.3; 14.3)	0.84 (0.69; 0.92)
CRO	*PP L CON*	1699.9 (476.5)	1719.4 (433.8)	98.8 (71.6; 159.1)	9.6 (6.9; 15.9)	0.91 (0.72; 0.97)
	PP L ECC	1701.7 (417.4)	1862.2 (423.3)	99.8 (72.4; 160.8)	10.5 (7.5; 17.4)	0.89 (0.70; 0.96)
	PP R CON	1600.5 (390.3)	1742.7 (422.7)	89.5 (64.9; 144.2)	9.1 (6.5; 15.0)	0.91 (0.74; 0.97)
	PP R ECC	1713.1 (441.4)	1812.3 (375.4)	156.3 (113.3; 251.7)	13.2 (9.4; 22.2)	0.71 (0.30; 0.90)

Note: SHL: shuffle lateral step with iso-inertial device; CRO: lateral crossover step with iso-inertial device; TEM: typical error of measurement; CI: confidence interval; CV: coefficient of variation; ICC: intraclass correlation coefficient; PP L CON: peak power with left leg in the concentric phase; PP L ECC: peak power with left leg in the eccentric phase; PP R CON: peak power with right leg in the concentric phase; PP R ECC: peak power with right leg in the eccentric. phase

Table 3: Spearmans *r* correlations between inter-limb asymmetry scores and unilateral jump performance.

Asymmetry Variable	**SLCMJ**		**SLBJ**		**SLLJ**	
	D	*ND*	*D*	*ND*	*D*	*ND*
SLCMJ	0.14	-0.24	-0.05	-0.02	0.06	0.09
SLBJ	0.11	0.07	0.26	0.09	0.30	0.15
SLLJ	-0.17	-0.18	0.13	0.01	0.13	-0.13
CODS	-0.50*	-0.53*	-0.22	-0.30	-0.13	-0.20
SHL-C	0.20	0.16	0.13	0.10	0.03	0.10
SHL-E	0.14	0.28	0.06	0.01	0.02	-0.07
CRO-C	-0.01	-0.08	0.14	0.09	0.15	0.02
CRO-E	-0.01	-0.04	-0.08	-0.03	0.03	0.04

* significant correlation at $p < 0.05$

CODS: Change of direction speed; SLCMJ: Single leg countermovement jump; SLBJ: Single leg broad jump; SLLJ: Single leg lateral jump; SHL: Shuffle lateral step with iso-inertial device; CRO: Crossover with iso-inertial device; C: Concentric; E: Eccentric; D: Dominant leg; ND: Non-dominant leg

Table 4: Spearmans *r* correlations between inter-limb asymmetry scores and change of direction speed performance.

Asymmetry Variable	CODS		SHL-C		SHL-E		CRO-C		CRO-E	
	D	*ND*	*D*	*ND*	*D*	*ND*	*D*	*ND*	*D*	*ND*
SLCMJ	0.01	0.05	0.30	0.28	0.20	0.25	0.05	0.10	0.19	0.13
SLBJ	0.02	0.02	0.12	0.08	0.17	0.10	0.16	0.04	0.16	0.13
SLLJ	0.07	0.06	-0.08	-0.03	-0.01	0.01	-0.06	-0.13	-0.09	-0.03
CODS	0.50*	0.63**	-0.10	-0.09	-0.10	0.05	-0.25	-0.21	-0.29	-0.31
SHL-C	0.02	-0.02	0.26	0.05	0.16	0.01	0.33	0.28	0.32	0.36
SHL-E	-0.01	-0.11	0.09	0.03	0.14	-0.16	0.25	0.15	0.21	0.15
CRO-C	0.01	0.05	0.20	0.21	0.19	0.27	0.26	0.02	0.28	0.16
CRO-E	0.03	0.06	0.16	0.16	0.12	0.08	0.08	-0.04	0.22	-0.03

** significant correlation at $p < 0.01$; * significant correlation at $p < 0.05$

CODS: Change of direction speed; SLCMJ: Single leg countermovement jump; SLBJ: Single leg broad jump; SLLJ: Single leg lateral jump; SHL: Shuffle lateral step with iso-inertial device; CRO: Crossover with iso-inertial device; C: Concentric; E: Eccentric; D: Dominant leg; ND: Non-dominant leg

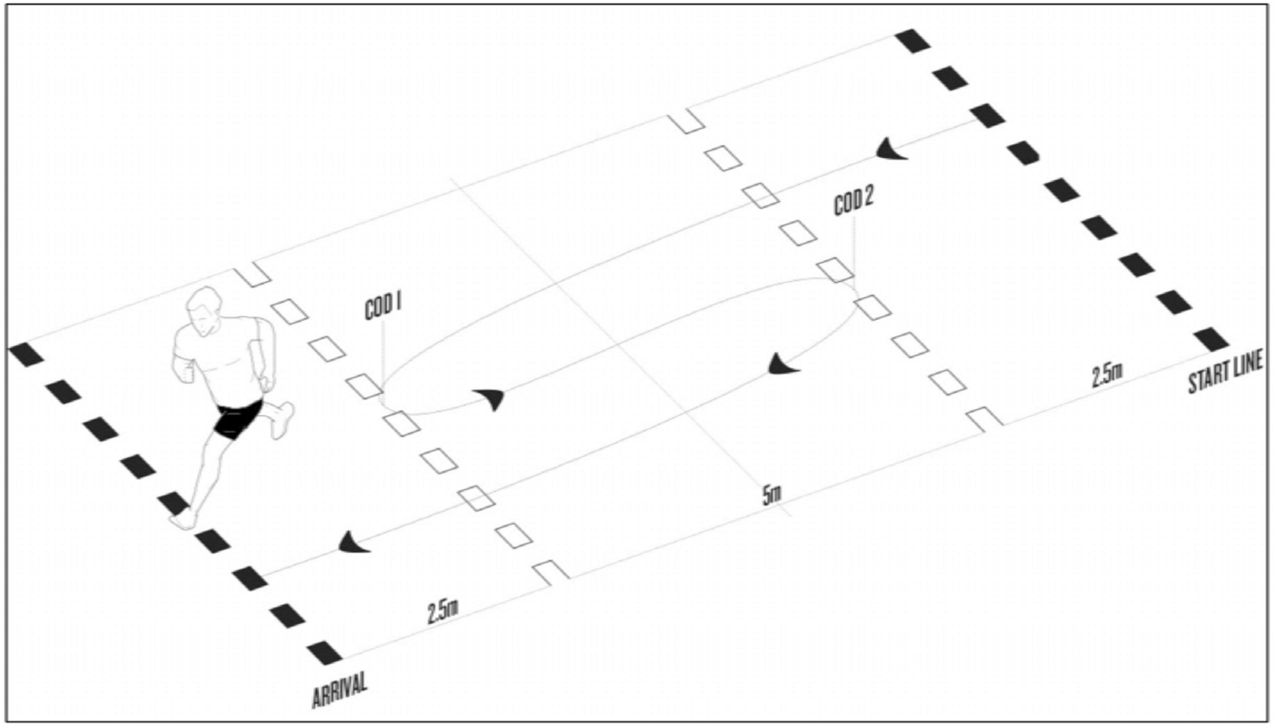

Figure 1. Testing conducted on field court. Testing conducted by double change of direction speed with the same leg.

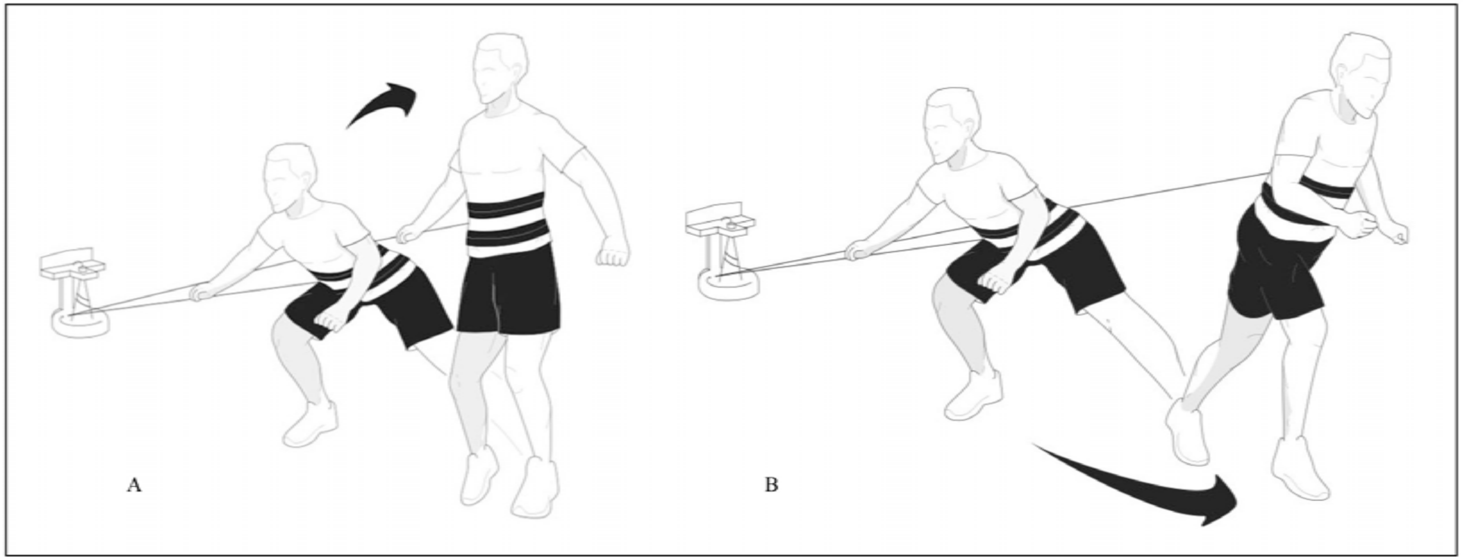

Figure 2: Testing conducted on the iso-inertial device. A = Shuffle lateral step (phase start and brake); B = Crossover step (phase start and brake with the right leg)

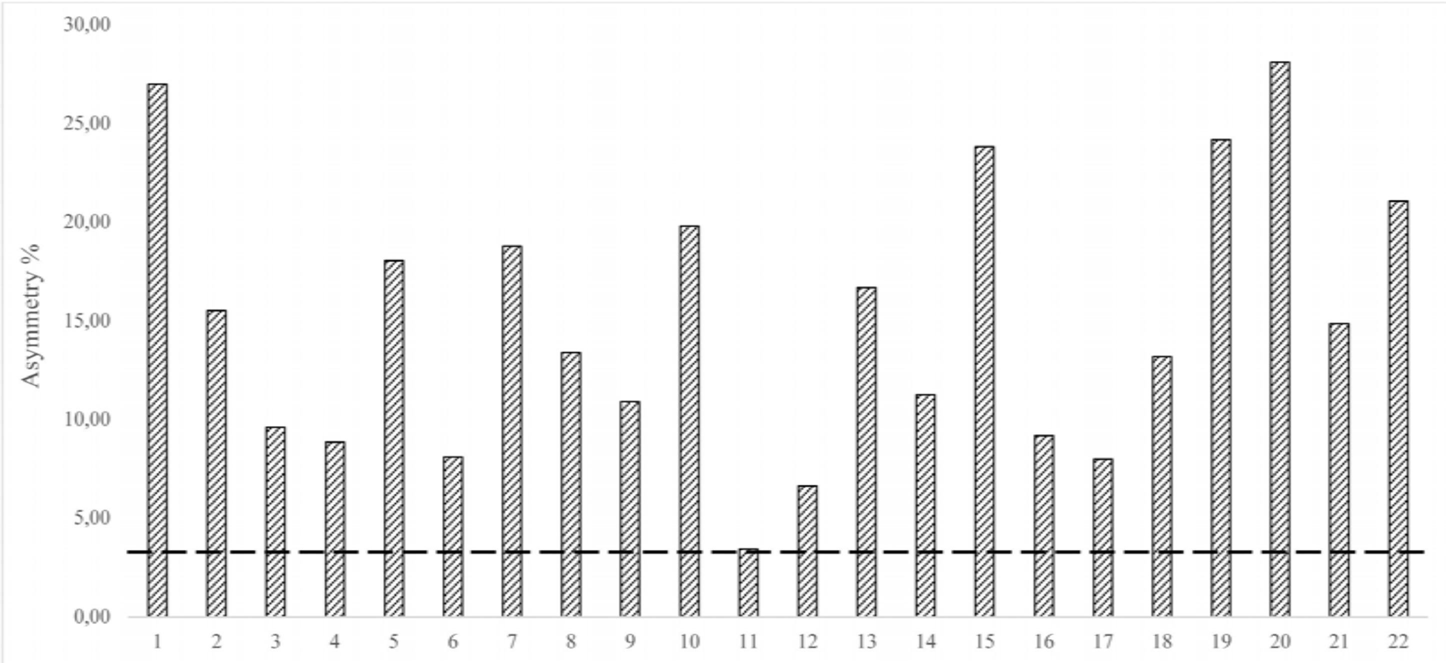

Figure 3: Individual asymmetry scores for the single leg countermovement jump. Note: dotted line represents group threshold of 3.60% calculated from the pooled CV of right and left limb test scores.

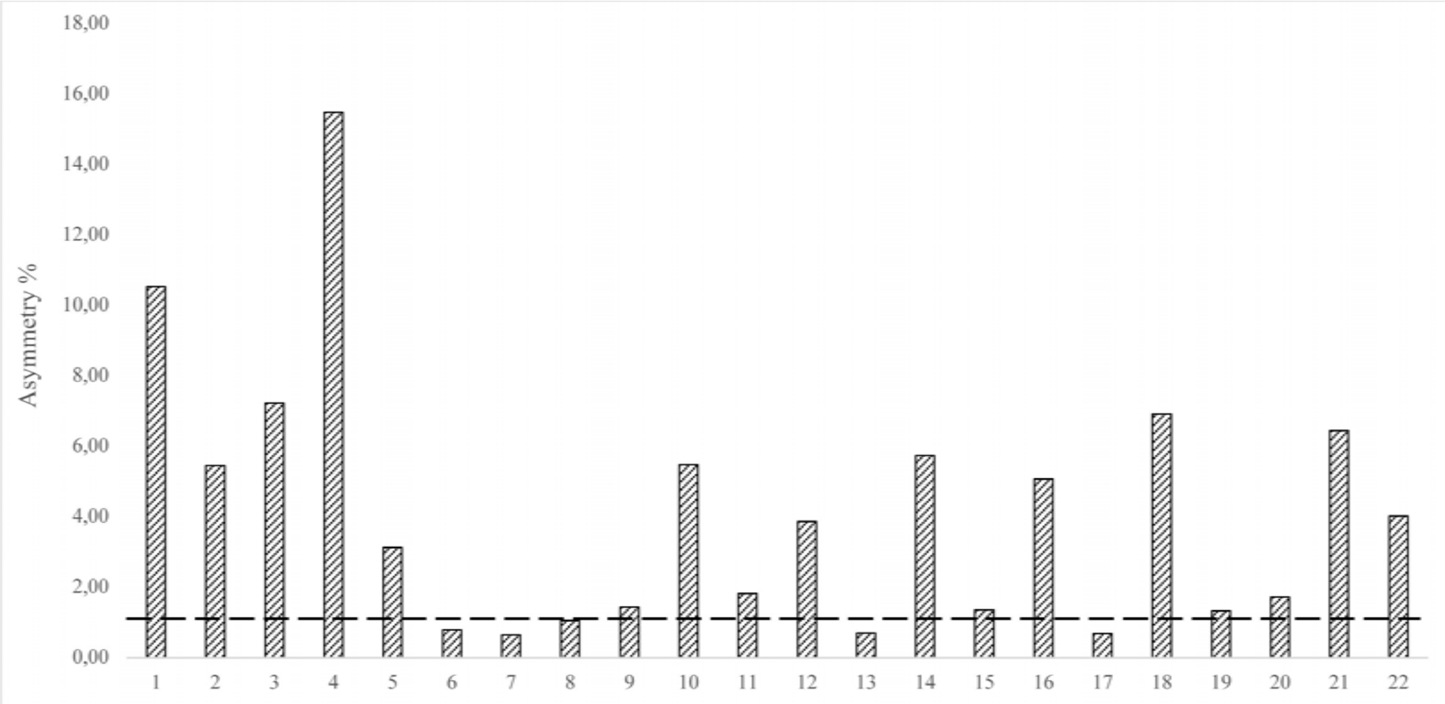

Figure 4: Individual asymmetry scores for the single leg broad jump. Note: dotted line represents group threshold of 1.13% calculated from the pooled CV of right and left limb test scores.

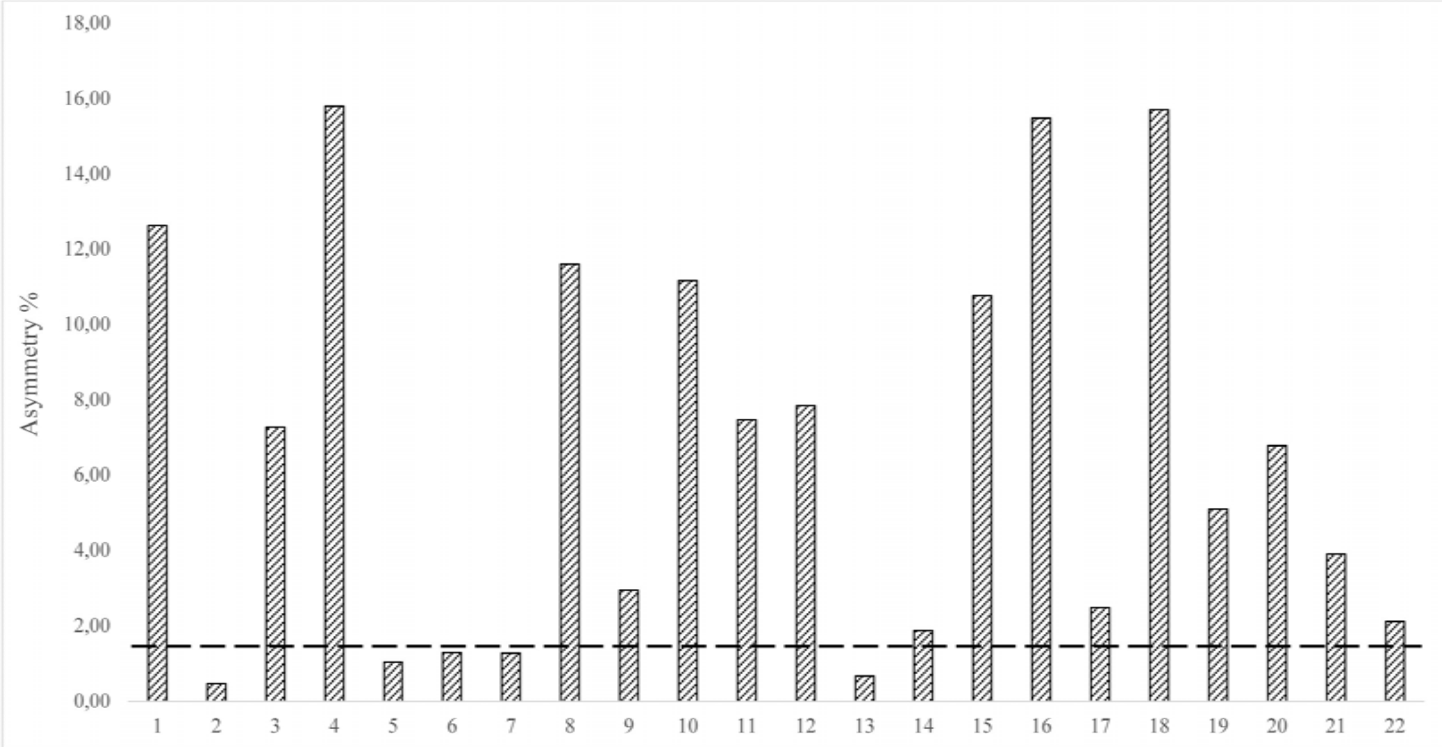

Figure 5: Individual asymmetry scores for the single leg lateral jump. Note: dotted line represents group threshold of 1.87% calculated from the pooled CV of right and left limb test scores.

STUDY 4

Relationship Between Inter-limb Asymmetries and Speed and Change of Direction in Youth Handball Players

Citation:

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Abstract study 4

The aims of the present study were to quantify inter-limb asymmetry from jumping, change of direction speed (CODS) and iso-inertial tests and to establish the association between those asymmetry scores and performance during speed and CODS tests in youth handball athletes. Twenty-six youth handball players (age: 16.2 ± 0.9 years) volunteered to participate in this study and performed single leg countermovement jumps (SLCMJ), broad jumps (SLBJ), lateral jumps (SLLJ), CODS tests at 180° (CODS180) and 90° (CODS90), change of direction actions with iso-inertial overload (crossover step (CRO) and lateral shuffle step (LSS)) and 20 m sprint test. Excellent ICC values were found for all tests (ICC = 0.96-1.00) with the exception of the dominant limb during the CODS90 test (ICC = 0.69). Inter-limb asymmetry scores ranged from 3.66-12.67%. Iso-inertial asymmetry values were higher than those found during jumping tasks (9.8-12.7% vs. 3.66-8.76%). Spearman's *r* correlations showed significant relationships between CRO asymmetry and CODS90 performance on both limbs (r = 0.48-0.51; $p < 0.05$) and CODS180 (r = 0.41-0.51; $p < 0.05$) and sprint test ($r = 0.46$; $p < 0.05$). These results show the test-specific nature of asymmetries in youth handball players, with iso-inertial device and CODS deficit presenting the greatest magnitude of asymmetries. Furthermore, inter-limb differences during iso-inertial device (CRO) were associated with reduced CODS and sprint performance. These results suggest that the use of iso-inertial devices for the detection of inter-limb asymmetry may be more effective than total time during traditional CODS tests and that larger imbalances are associated with reduced athletic performance in youth handball players.

Key Words: iso-inertial; jumping; symmetry; youth athletes

Introduction

Handball is a sport requiring endurance, strength, speed and coordination (37), with several high intensity actions during matches such as jumps, accelerations, decelerations and change of direction speed (CODS), all within the context of attacking and defending (18,31). These situations demand movement proficiency in multiple directions which are underpinned by high levels of plyometric ability (7) and sport-specific skills (31). Of the total distance covered in a match (~3600 m), 18.4% has been suggested to be performed laterally (25). For this reason, displacements in the frontal plane have a critical role in handball performance. Further to this, a specific emphasis has been suggested on the relevance of changing direction during side-stepping movements during matches (25,31). However, empirical studies investigating sport-specific movements in youth handball athletes are scarce; thus, further research in this area is required.

Recently, there has been a rise in the number of studies investigating the association between inter-limb asymmetry and measures of athletic performance. For example, Lockie et al. (20) reported between-limb differences for jump height of 10.4% during the single leg countermovement jump (SLCMJ), and distance of 3.3 and 5.1% during the single leg broad jump (SLBJ) and single leg lateral jump (SLLJ) tests respectively in male collegiate athletes. However, no significant correlations were reported between asymmetry and speed or CODS. Similarly, Dos'Santos et al. (11) reported mean inter-limb differences of 5-6% for jump distance during the single and triple hop tests in male collegiate athletes, and also showed no significant relationships with total time during two

CODS tests. In contrast, Bishop et al. (5) showed that jump height asymmetry (12.5%) from the SLCMJ was associated with slower 5 m ($r = 0.49$; $p < 0.05$), 10 m ($r = 0.52$; $p < 0.05$) and 20 m ($r = 0.59$; $p < 0.01$) sprint performance in youth female soccer players. In addition, Bishop et al. (6) showed that drop jump asymmetries were associated with slower acceleration, speed and CODS performance in adult female soccer players. Specifically, drop jump height asymmetry was correlated with 30 m ($r = 0.58$; $p < 0.05$) and 505 on both limbs ($r = 0.52 - 0.66$; $p < 0.05$), and reactive strength index asymmetry was correlated with 10 m ($r = 0.52$; $p < 0.05$) and 505 on both limbs ($r = 0.54 - 0.55$; $p < 0.05$). Thus, with conflicting literature surrounding the association between asymmetry and speed and CODS, further research on this topic is warranted.

As the aforementioned information on asymmetry shows, many studies have quantified side-to-side differences using jump tests. However, owing to the amount of lateral movement patterns in handball, assessing between-limb asymmetries during CODS tests could also be considered a valid test protocol. Hart et al. (15) assessed between-limb deficits during an agility test where the test was completed in ‘both directions’ using 58 sub-elite Australian rules players. Mean asymmetry was 8.2% for right foot dominant players and 8.0% for left foot dominant players. More recently though, it has been suggested that the measure of total time may actually mask the true ability of an athlete to perform a CODS task (28,29), and that isolating the change of direction itself may be a more useful measure of CODS performance. This can be achieved by subtracting the time taken to complete a linear sprint (e.g., 10 m) from the total time taken to complete a CODS test of equal distance (e.g., 505); a concept known as the "change of direction deficit" (CODD). Where asymmetry is concerned, this notion was supported by Dos'Santos et al. (12) who showed that only 2 out of 43 netball athletes displayed asymmetries > 10% when using total time as the outcome measure during the 505 test. Conversely, 21 athletes showed between-limb differences > 10% when using the CODD. To the authors' knowledge, additional literature relating to asymmetry for both total time and the CODD does not exist; thus, further research in this area is also required.

Recently, iso-inertial devices have been suggested to be a viable method for training athlete populations (13,32,35), and in some instances more so than traditional weight training when aiming to improve velocity, acceleration and eccentric force (30,35). De Hoyo et al. (17) showed squat training on an iso-inertial device improved crossover and side step cutting actions in soccer players and Tous-Fajardo et al. (36) showed positive effects in CODS performance after the introduction of multidirectional training with an iso-inertial pulley in youth soccer players. From an asymmetry perspective, there is a paucity of literature investigating the use of iso-inertial devices to both detect and reduce inter-limb differences. Madruga-Parera et al. (22) showed that isolating specific CODS actions with an iso-inertial device (e.g., crossover and side steps) was a useful tool at detecting asymmetries, especially in comparison to CODS tests (CODS asymmetry = 1.8%; iso-inertial CODS asymmetry = 7.4-11.2%). However, to the authors' knowledge, additional studies pertaining to asymmetry from iso-inertial devices is scarce; thus, further research is again warranted.

Owing to the conflicting results of how asymmetry impacts athletic performance and the prevalence of these between-limb differences during CODS tasks, the aims of the present study were twofold: 1) to utilize a fitness test battery which quantifies inter-limb asymmetry from jumping, CODS and iso-inertial tests and, 2) to establish the association between those asymmetry scores and performance during speed and CODS tests in youth handball athletes.

Methods

Experimental approach to the problem

The current study employed eight tests to provide fitness data for youth handball players. These tests measured unilateral jump performance (during vertical, horizontal and lateral directions), CODS performance (inclusive of 90° and 180° turns), muscle power in specific CODS actions: lateral shuffle step (LSS) and crossover step (CRO) performed by iso-inertial resistance, and linear speed (via a 20 m sprint test). Recently, several studies have noted the task-specificity of asymmetry and suggested that more than a single test must be used to profile muscular imbalances (2,3,21); thus, multiple tests were used to profile both physical fitness and inter-limb asymmetry in this youth athlete population. Associative analysis was also conducted enabling a greater understanding of the relationships between asymmetry and CODS and speed performance in youth handball players.

Subjects

Twenty-six male youth handball players volunteered to participate in this study (age: 16.2 ± 0.9 years; post peak height velocity: 2.5 ± 0.8 years; height: 1.76 ± 0.60 m; body mass: 78.2 ± 12.4 kg) Subjects were eligible for inclusion if they had > 5 years of competitive handball experience, 2 years of experience in resistance training and were excluded if they presented any injury (overuse or acute) at the time of testing. All players were actively participating in high level youth handball league, performing 3 sessions per week, each lasting approximately 120 minutes per session and a match per week. All testing was completed during the third month of the competition period (nine month season). Written informed consent and assent were obtained from participants and their parents. This study was approved by the [** DELETED FOR PEER REVIEW **] ethics committee.

Procedures

Subjects arrived at a sports academy prior to the first training session of the week having been instructed not to eat for the preceding 2 hours and avoid caffeine consumption for at least 24 hours before the tests. All athletes were previously familiarized with the testing procedures due to their regular physical assessments throughout the handball season. Subjects were tested in two separate days, each separated by 72 hours.

Day one consisted of three unilateral jump tests and the CODS and sprint tests. On day two, players performed the specific change of direction actions with the iso-inertial device, owing to the likelihood of it impacting the performance of other tests if conducted on the same day. Each subject went through a specific warm up procedure consisting of five minutes of light jogging and dynamic stretches for the lower body (such as multi-directional lunges, inchworms, bodyweight squats, and spidermans). Upon completion, three practice trials were provided for each test where subjects were instructed to perform them at 75, 90 and 100% of their perceived maximal effort. Three minutes rest was given between the last practice trial and the start of the first test. For the change of direction test with iso-inertial resistance, an incremental procedure was performed (33). The researchers involved in this study randomized the use of players´ starting leg in each test. The reliability of all tests is presented in Table 1.

Single leg countermovement jump (SLCMJ). The SLCMJ was conducted on a contact mat (Chronojump, Boscosystem, Barcelona, Spain) measuring jump height in centimetres (cm). Subjects were required to step onto the center of the contact mat with one leg and place their hands on their hips (22). When ready, subjects performed a countermovement to a self-selected depth before accelerating as quickly as possible into a unilateral vertical jump, following the instructions to "jump as high as you can". The non-jumping leg was slightly flexed at the knee with the foot hovering next to the ankle of the jumping leg. No additional swinging of the non-jumping leg was allowed during the jump and hands were required to remain fixed at the hips. Any deviations from these criteria resulted in a void trial and subsequently retaken. Three trials were performed on each leg with 60-seconds rest provided between each trial. The highest jump on each leg was then used for subsequent data analysis

Single leg lateral jump (SLLJ). The SLLJ measured lateral jump distance (in cm) with a standard measuring tape that was fixed to the floor. Subjects started just behind 0 cm with a selected test leg and performed a countermovement to a self-selected depth before jumping laterally as far as possible along the direction of the tape measure (without landing directly on it). For example, when starting on the left leg, subjects were instructed to jump to the right as far as they could with hands placed on hips throughout the test. Owing to the increased difficulty of this test (by virtue of jumping in the frontal plane), the landing was performed on both limbs to increase the chance of a stable landing. Subjects were required to stick the landing for 2-seconds with the distance measured from the outside edge of the landing foot (part of the foot closest to 0 cm). Three trials were performed on each leg with 60-seconds rest provided between each trial. The trial with the furthest jump on each leg was then used for subsequent data analysis.

Single leg broad jump (SLBJ). The SLBJ measured horizontal jump distance (in cm) with a standard measuring tape that was fixed to the floor. Subjects started with their toes just behind 0 cm with a selected test leg and performed a countermovement to a self-selected depth before jumping as far forward as possible along the direction of the tape measure (without landing directly on it) with hands placed on the hips throughout. Similar to the SLLJ, owing to the increased difficulty of this test, the landing was performed on both limbs to increase the chance of a stable landing. Subjects were required to stick the landing for 2-seconds with the distance measured from the heel of the jumping foot. The non-jumping leg was slightly flexed at the knee with the foot hovering next to the ankle of the jumping leg. No additional swinging of the non-jumping leg was allowed during the jump. Any deviations from these criteria resulted in a void trial and subsequently retaken. Three trials were performed on each leg with 60-seconds rest provided between each trial. The furthest jump on each leg was then used for data analysis.

90º Change of Direction Speed test (CODS90). CODS90 test was previously validated by Maloney et al. (23) who reported intraclass correlation coefficients (ICC) of 0.95 within-session and 0.97 between-sessions (Figure 1). To perform this test, subjects were instructed to conduct two 90º changes of direction with the same leg, for a total distance of 20 m. The first change of direction was performed after a distance of 6.66 m, whereby the subject then sprinted 6.66 m before the second 90º change of direction, and subsequently sprinted another 6.66 m to finish the test. Total time in the CODS test was measured with photocell beams connected to a computer (Chronojump Boscosystem, Barcelona, Spain). The fastest time of the three trials for each leg was used for data analysis and a trial was considered successful if the player performed a clear change of direction action. Each trial was separated by a 180-second recovery period.

** PLEASE INSERT FIGURE 1 ABOUT HERE **

180º Change of Direction Speed test (CODS180).

Subjects performed two 180º changes of direction using the same leg in each trial (dominant or non-dominant leg), for the CODS180-D or CODS180-ND, respectively (Figure 2) (22). The first change of direction was performed after 7.5 m from the start, and the second one was performed after 5 m from the first change of direction. The subjects sprinted a total distance of 20 m. Total time in the CODS test was measured with photocell beams (Chronojump Boscosystem, Barcelona, Spain). The fastest time of the three trials for each leg was used for analysis. A trial was considered successful if the entire foot crossed over the line while changing direction. Each trial was separated by a 180-second recovery period.

** PLEASE INSERT FIGURE 2 ABOUT HERE **

20m sprint test. Total time in the sprint test was measured with photocell beams, placed on the starting line and at 20 m which was connected to a laptop (Chronojump Boscosystem, Barcelona, Spain). The front foot was placed 0.3 m before the first set of photocells to ensure that the beam was not broken until each trial began. The fastest time of the three trials was used for analysis. Each trial was separated by a 180-second recovery period.

Change of direction with iso-inertial resistance. Subjects stood beside a conical pulley (CP), an iso-inertial device (Byomedic System SCP, Barcelona, Spain) of a metal flywheel (diameter: 0.42 m) with up to 16 masses (0.421 kg and 0.057 m diameter each one). A fixed axis is located at the center of the beam around which the masses rotate. The moments of inertia were 0.12 kg_m2 and 0.27

kg_m2 for 4 and 16 masses respectively. The modification of the moment of inertia is made by adding any number of the 16 masses on the edge of the flywheel and also by selecting four positions (P1, P2, P3 or P4), changing the location of the pulley that is closest to the cone (26).

Subjects are familiar with the device and the type of tasks, since it is part of their training in the area of strength and performance (2 years of experience, 1 session per week). Subjects were instructed to perform an incremental test to register the maximum power score, set to the maximum point of the power curve, the maximum power test was recorded by (Chronojump Boscosystem, Barcelona, Spain). Every set with a different load was stopped by two possibilities: either by completing eight repetitions or by a decrease of 10% of the maximum value of the set. The test started with 10 masses, and 2 masses were added until that a maximal power outcome was found. For the present sample, only P1 position was necessary to achieve the maximum power. The performed actions were lateral shuffle step (LSS) (Figure 3A), and crossover step (CRO) (Figure 3B). Concentric (C) action is identified by the acceleration phase, while the eccentric (E) one is related to the deceleration phase. Both phases were analyzed.

The attempt was considered valid if the subject located at 1m from the conical pulley and performing the task with maximum effort. In the LSS the subject was instructed to perform a lateral lunge in the frontal plane. The movement began with the feet aligned in this plane and the leg closer to the CP flexed to approximately 100°-120°. Then, repeated lateral shuffle steps of maximum intensity were demanded, without allowing hip rotation. For the CRO test, the movement began with the feet aligned in the frontal plane and the leg closer to the CP flexed to approximately 100°-120°. The action consisted of a crossover step performed at maximum intensity, pivoting on the farthest foot from the CP by a rotation of the whole body. While doing this action, the nearest leg (regarding to the CP) advanced over the pivoting one in the sagittal plane, and keeping the hips and shoulders at the same height during the step. At the end of this acceleration phase, the subject returned to the starting position with the feet aligned in the frontal plane. Each trial was separated by a 180-second recovery period.

** PLEASE INSERT FIGURE 3 ABOUT HERE **

Statistical Analysis

All data was recorded as mean and standard deviations. Data were analyzed by IBM SPSS Statistics for Windows version 22.0 (Armonk, NY: IBM Corp). The Shapiro-Wilk test was used to determine whether data were normally distributed. Data not following a normal distribution were root square-transformed before further analysis. The reliability was tested by a two-way random ICC with absolute agreement and 95% confidence intervals, typical error of the measurement (TEM), and coefficient of variation (CV). For interpretation, acceptable CV values were considered ≤ 10% (9) and intraclass correlation coefficient (ICC) were interpreted in line with Koo and Li (19), where values > 0.9 = excellent, 0.75 - 0.9 = good, 0.5 - 0.75 = moderate and < 0.5 = poor.

Mann Whitney-U tests were used to examine performance differences between limbs. A one-way analysis of variance (ANOVA) with repeated measures was performed to assess differences in neuromuscular asymmetries between performance tests and Bonferroni post hoc test was used to aid interpretation of the results where significant differences occurred. Statistical significance was set at $p < 0.05$. Cohen's *d* effect sizes were calculated for pairwise comparisons which were computed as the mean difference divided by the pooled standard deviation and defined as: small (< 0.2), moderate (0.2-0.5), and large (> 0.8) mean differences (8).

Spearman's rank correlation coefficients (*r*) were computed to assess the relationship between inter-limb asymmetry scores and performance for all tests. The following criteria were adopted for interpreting the magnitude of correlation between test measures: ≤ 0.1 (trivial); 0.1-0.3 (small); 0.3-0.5 (moderate); 0.5-0.7 (large); 0.7-0.9 (very large) and 0.9-1.0 (almost perfect) (16) CODD was calculated utilizing a similar method from Nimphius et al. (29) to examine if CODS90 and CODS180 times and CODD provided different indications of CODS ability. Z-scores were calculated by the formula: (individual subject score – group mean score)/SD. Worthwhile differences were also calculated (differences in z-scores for 90° and 180° time and CODD) following the methods described by Nimphius et al. (29). Inter-limb asymmetries were calculated for all tasks defining the dominant (D) (the limb with the better score) and non-dominant (ND) limb using the formula: 100/(maximum value)*(minimum value)*-1+100 (4), noting that this has been suggested as an appropriate method for calculating inter-limb differences from unilateral tests.

Results

Asymmetries and test reliability data are presented in Table 1. ICC values were reported *good* to *excellent* for all tests with the exception of the D limb during the CODS90 test (ICC = 0.69). CV values were reported for all tests, some tests such as LSS E-ND did not report an acceptable CV (>10%). Asymmetries during SLBJ, CODS90 and CODS180 were significantly lower ($p < 0.05$) than asymmetries during the CODD90, CRO-C, CRO-E, LSS-C, LSS-E. In addition, CODS180 asymmetry was also significantly lower ($p < 0.05$) than CODD180 asymmetry, whereas SLCMJ asymmetry was significantly greater ($p < 0.05$) than SLBJ, CODS90 and CODS180 asymmetries. While SLLJ asymmetry was significantly lower ($p < 0.05$) than CRO-C asymmetry, it was significantly greater ($p < 0.05$) than CODS180 asymmetry. Furthermore, CODS180 asymmetry was significantly lower ($p < 0.05$) than LSS-E asymmetry. It is worth noting that all iso-inertial asymmetry values were higher than those found during jumping tasks (9.8-12.7% vs. 3.66-8.76%).

** PLEASE INSERT TABLE 1 ABOUT HERE **

Table 2 shows the correlations between asymmetries and speed and CODS performance. CRO-C asymmetry was significantly correlated with both CODS tests (on both limbs) as well as 20m sprint performance ($r = 0.46$; $p < 0.05$). Concentric power asymmetry during the LSS was correlated with CODS90 on the ND limb ($r = 0.44$; $p < 0.05$). Additional significant correlations were present between SLLJ asymmetry and CODS180 on the ND limb ($r = 0.39$; $p < 0.05$), CODS180 asymmetry and CODS180 on the ND limb ($r = 0.42$; $p < 0.05$), and CODD180 asymmetry and CODS180 on the ND limb ($r = 0.46$; $p < 0.05$). Owing to the variable nature of asymmetry, individual data of subjects been included for reported differences during jump, change of direction speed and iso-inertial change of direction tests (Figures 4-6).

** PLEASE INSERT TABLE 2 ABOUT HERE **

** PLEASE INSERT FIGURES 4-6 ABOUT HERE **

Discussion

The aims of the present study were twofold: 1) to utilize a fitness test battery which quantifies inter-limb asymmetry from jumping, CODS and iso-inertial tests and, 2) to establish the association between those asymmetry scores and performance during speed and CODS tests in youth handball athletes. Results showed different magnitudes of asymmetry among tests, with the CODD90 and iso-inertial assessments showing the greater asymmetry values. Larger asymmetry during the iso-inertial CRO was associated with reduced performance during CODS and sprint tests.

The first point to consider from these results is that significant differences between D and ND limbs were evident in all tests (ES range: 0.26-0.84). These results show that in youth handball, limb dominance can be expected and may lead to notable differences in performance between limbs during jumping and CODS tasks. Given the significance of these differences, practitioners are advised to monitor individual limb differences in line with previous suggestions (2), to ensure that deficits do not become too apparent, given they have previously been shown to be a by-product of competing in a single sport over time (14).

When handball demands are considered, jumping is one of the most common athletic actions (31); thus, represents an ecologically valid method of assessment for both performance monitoring and the detection of inter-limb asymmetries. In the present study, results showed that the SLCMJ was able to detect larger between-limb differences (8.76%) than the SLBJ (3.66%) and SLLJ (5.97%) tests, which agrees with previous research reporting jumping asymmetries (5,20). Therefore, if practitioners wish to profile an athlete's existing side-to-side imbalances, it appears that the SLCMJ may offer a useful method when unilateral jump tests are considered.

Another interesting finding of the present study is the magnitude of asymmetry for CODS and the CODD. Previous literature has described the CODD as a way of isolating the actual CODS action (12,29); however, little is known about the prevalence of asymmetries using this metric. Significantly larger asymmetries were shown when using the CODD compared to the total time in the equivalent CODS test. For example, inter-limb differences for the CODS90 were 3.39%, but 10.52% for the CODD90. Likewise, the CODS180 test showed differences of 2.12%, but the CODD180 highlighted imbalances of 5.48%. These values are comparable to Dos'Santos et al. (12), who reported mean asymmetries of -2.3% for the 505 test, but -11.9% for the 505 CODD. Further to this, the importance of angles in CODS actions has been previously indicated by Dos'Santos et al. (10), highlighting the requirement for greater braking strategies during CODS angles > 135°. However, in the present study, larger between-limb differences were actually seen during the CODS90 test. Given the paucity of literature comparing CODD at different angles, this is challenging to fully explain. However, it is possible that because of the smaller change of direction during 90°, that discrepancies in limb dominance were more evident due to the requirement for reduced braking strategies compared to 180° (10). In essence, when turning 180°, athletes have no option but to brake effectively because of the maximal angles required when changing direction. In contrast, less braking is required during 90° which may highlight larger between-limb differences. However, it is worth noting that more in-depth analysis of CODS performance is required to fully corroborate this theory.

Where iso-inertial tests are concerned, results from the present study showed notable asymmetries ranging from 9.80-12.67%, which were significantly greater than the differences in the CODS90 and CODS180 tests. Literature reporting between-limb differences from iso-inertial methods is scarce; however, Madruga-Parera et al. (22) evaluated CODS asymmetries from an iso-inertial device in young tennis players, and reported values ranging 7.35-9.82% in the LSS and 9.31-11.18% in the CRO. These figures represent similar values to those shown in the present study and highlight the suitability of this method to detect asymmetries in both youth tennis and handball populations in comparison to CODS tests. In addition, given the significantly larger asymmetries of iso-inertial and CODD (isolated CODS actions) comparing to CODS tests (non-isolated CODS action), it is plausible to suggest that total time during CODS tests is not a very sensitive metric at detecting existing side-to-side asymmetries. According to our results, iso-inertial tests could be added to the CODD registered by Dos'Santos et al. (12) in order to acquire more specific information about isolated CODS asymmetries. Thus, if targeted training interventions are deemed necessary, then it is likely that specific training drills focusing on these movements are required to show technical proficiency on both limbs. Consequently, iso-inertial training has been described as a useful method to improve strength and performance (13,30), especially when multidirectional tasks with eccentric overload are designed (13). Furthermore, previous studies have shown the importance of the trunk activation by virtue of improved throwing velocity in handball players (24,34). Thus, although not investigated in the present study, it seems apparent that improved trunk strength may enhance throwing performance, most likely due to greater sequential force transference through the kinetic chain during the action of throwing.

Another important finding of the present study is the significant correlation between the concentric phase asymmetry of CRO test and reduced performance in 20 m sprint, CODS90 and CODS180 on both limbs (Table 2). Firstly, all significant correlations are positive, indicating that larger asymmetries are associated with slower times during speed and CODS tests. Again, although challenging to fully explain, this is in agreement with numerous studies on the topic of asymmetry and athletic performance. Recent work has shown that larger asymmetries are also associated with reduced speed (1,3,5,6) and CODS performance (1,6,23). This adds further evidence that inter-limb asymmetries may be detrimental to measures of athletic performance, which practitioners may wish to consider when designing training programmes for athletes that are required to be proficient in multiple planes of movement (e.g., team and court sport athletes).

Significant correlations were also established between concentric phase asymmetry of the LSS and CODS90 on the ND limb ($r = 0.44$; $p < 0.05$) test, but not in the CODS180 assessment. This represents an important finding given that only asymmetry during the concentric actions of the CRO and LSS movements showed significant associations with reduced speed and CODS performance. As such, if practitioners wish to profile their athletes' side-to-side differences using iso-inertial tests, concentric-based movements may be the most appropriate to monitor (22). Additional significant correlations were also shown between SLLJ asymmetry and CODS180 on the ND limb ($r = 0.39$; $p < 0.05$), CODS180 asymmetry and CODS180 on the ND limb ($r = 0.42$; $p < 0.05$) and CODD180 asymmetry and CODS180 on the ND limb ($r = 0.46$; $p < 0.05$). Thus, given the volume of correlations associated with slower speed and CODS performance in the present study, it is suggested that youth handball players may wish to reduce existing side-to-side imbalances to optimize athletic performance.

Despite the usefulness of these findings, this study presents some limitations. There is a lack of knowledge of the 'most suitable' iso-inertial load to achieve the most representative CODS action in sport. Related to this limitation, future research is needed combining the use of force platform both with CODS iso-inertial and CODS tests at different speeds (to obtain a scale of force values), since ground reaction forces could be an adequate parameter to link the intensity of both tests. Moreover, multi-axial force platforms would detect the horizontal force vector in an isolated way, and this parameter is a fundamental factor when aiming to optimize acceleration and speed abilities (21,27).

Practical Applications

This study offers the possibility to apply functional and specific assessments for youth handball players in order to identify the nature of inter-limb asymmetries. In addition, it is important to highlight the importance to isolate the change of direction action to highlight existing asymmetries of this motor skill. Practitioners should consider the iso-inertial tests considered in this research and the CODD in order to inform training programs and aim to optimize CODS performance. Furthermore, according to the asymmetries shown in this study, and the established relationships with performance, it is suggested that training programs should consider the reduction of inter-limb asymmetries in youth handball populations.

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TABLES AND FIGURES
STUDY 4

Table 1. Mean test scores, effect sizes, inter-limb asymmetry values and test reliability data.

Performance Test	Mean ± SD	Effect Size	Asymmetry (%)	TEM (95% CI)	CV (%)	ICC (95%CI)
SLCMJ-D (cm)	19.05 ± 3.78*	0.48	8.76 ± 4.80	0.52 (0.41-0.72)	2.4 (1.9-3.3)	0.98 (0.96-0.99)
SLCMJ-ND (cm)	17.39 ± 3.65			0.38 (0.30-0.52)	2.3 (1.8-3.2)	0.99 (0.98-1.00)
SLBJ-D (cm)	168.77 ± 24.12*	0.26	3.66 ± 2.55	0.90 (0.70-1.24)	0.6 (0.4-0.8)	0.99 (0.98-1.00)
SLBJ-ND (cm)	162.58 ± 23.51			0.75 (0.58-1.03)	0.4 (0.4-0.6)	0.99 (0.98-1.00)
SLLJ-D (cm)	150.32 ± 22.86*	0.42	5.97 ± 5.05	1.40 (1.10-1.43)	1.0 (0.8-1.3)	0.98 (0.97-0.99)
SLLJ-ND (cm)	141.10 ± 20.76			3.30 (2.59-4.56)	2.2 (1.7-3.0)	0.98 (0.95-0.99)
CODS 90-D (s)	4.41 ± 0.29*	0.56	3.39 ± 2.72	0.13 (0.10-0.19)	2.7 (2.1-3.8)	0.69 (0.42-0.85)
CODS 90-ND (s)	4.57 ± 0.28			0.03 (0.03-0.05)	0.8 (0.6-1.1)	0.99 (0.97-0.99)
CODD 90-D (s)	1.28 ± 0.18*	0.84	10.52 ± 7.94	-	-	-
CODD 90-ND (s)	1.44 ± 0.20			-	-	-
CODS 180-D (s)	4.91 ± 0.27*	0.37	2.12 ±2.50	0.05 (0.04-0.07)	1.1 (0.9-1.6)	0.96 (0.92-0.98)
CODS 180-ND (s)	5.02 ± 0.31			0.04 (0.04-0.06)	0.9 (0.7-1.3)	0.98 (0.96-0.99)
CODD 180-D (s)	1.78 ± 0.14*	0.62	5.48 ± 6.21	-	-	-
CODD 180-ND (s)	1.88 ± 0.18			-	-	-
20m (s)	3.13 ± 0.25	-	-	0.04 (0.03-0.06)	1.3 (1.0-1.7)	0.98 (0.95-0.99)
LSS C-D (W)	467.47 ±140.45*	0.36	10.72 ± 8.35	56.6 (42.1-86.1)	12.9 (9.5-20.3)	0.70 (0.46-0.84)
LSS C-ND (W)	418.17 ± 130.60			48.5 (36.1-73.8)	13.0 (9.6-20.5)	0.72 (0.49-0.85)
LSS E-D (W)	504.54 ± 119.45*	0.57	12.67 ± 9.91	39.1 (29.1-59.5)	10.3 (7.5-16.0)	0.81 (0.54-0.93)
LSS E-ND (W)	438.11 ± 112.69			59.7 (44.4-90.9)	17.5 (12.8-27.8)	0.72 (0.49-0.85)
CRO C-D (W)	541.38 ± 189.11*	0.34	11.79 ± 7.24	40.0 (30.9-56.7)	9.9 (7.6-14.3)	0.87 (0.72-0.94)
CRO C-ND (W)	479.43 ± 167.36			49.4 (38.2-69.9)	11.1 (8.5-16.1)	0.79 (0.57-0.91)
CRO E-D (W)	463.01 ± 140.50*	0.35	9.80 ± 8.77	37.8 (29.2-53.5)	11.8 (9.0-17.1)	0.77 (0.58-0.88)
CRO E-ND (W)	415.36 ± 129.36			35.9 (27.7-50.8)	11.4 (8.7-16.5)	0.70 (0.46-0.84)

* = significantly different to non-dominant leg ($p < 0.001$)

SD = standard deviation; TEM = typical error of measurement; CI = confidence intervals; CV = coefficient of variation; ICC = intraclass correlation coefficient; cm = centimetres; W = watts; s = seconds; CODS = change of direction speed; SLCMJ = single leg countermovement jump; SLBJ = single leg broad jump; SLLJ = single leg lateral jump; LSS = lateral shuffle step with iso-inertial device; CRO = crossover step with iso-inertial device; C = concentric; E = eccentric; D = dominant leg; ND = non-dominant leg.

Table 2. Correlations between inter-limb asymmetries and change of direction (on both limbs) and 20 m sprint performance.

Asymmetry Tests	CODS90		CODS180		20 m
	Dominant	*Non-dominant*	*Dominant*	*Non-dominant*	
SLCMJ	-0.06	-0.16	0.18	0.21	0.18
SLLJ	0.21	0.29	0.28	0.39*	0.27
SLBJ	0.16	0.21	0.28	0.17	0.22
CODS90	-0.33	0.10	-0.20	-0.04	-0.21
CODD90	-0.35	0.07	-0.19	-0.02	-0.15
CODS180	-0.11	0.02	-0.01	0.42*	0.09
CODD180	-0.06	0.06	0.03	0.46*	0.15
CRO-C	0.48*	0.51**	0.51**	0.41*	0.46*
CRO-E	-0.16	-0.02	-0.08	-0.03	0.03
LSS-C	0.29	0.44*	0.28	0.31	0.27
LSS-E	-0.16	0.01	-0.06	0.18	-0.02

** significant correlation at $p < 0.01$; * significant correlation at $p < 0.05$

CODS: Change of direction speed; CODD: Change of direction deficit; SLCMJ: Single leg countermovement jump; SLBJ: Single leg broad jump; SLLJ: Single leg lateral jump; LSS: Lateral shuffle step with iso-inertial device; CRO: crossover with iso-inertial device; C: Concentric; E: Eccentric; D: Dominant leg; ND: Non-dominant leg

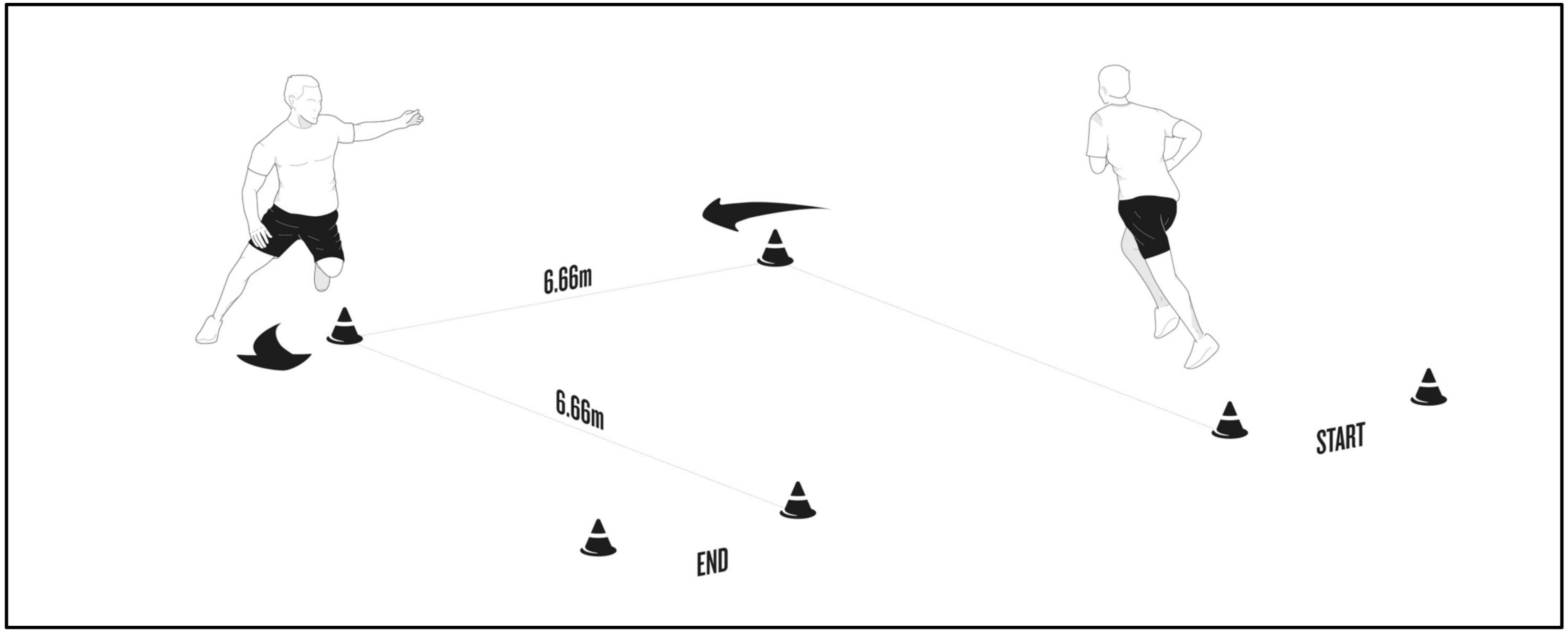

Figure 1. Schematic of the double 90º change of direction speed test (CODS90)

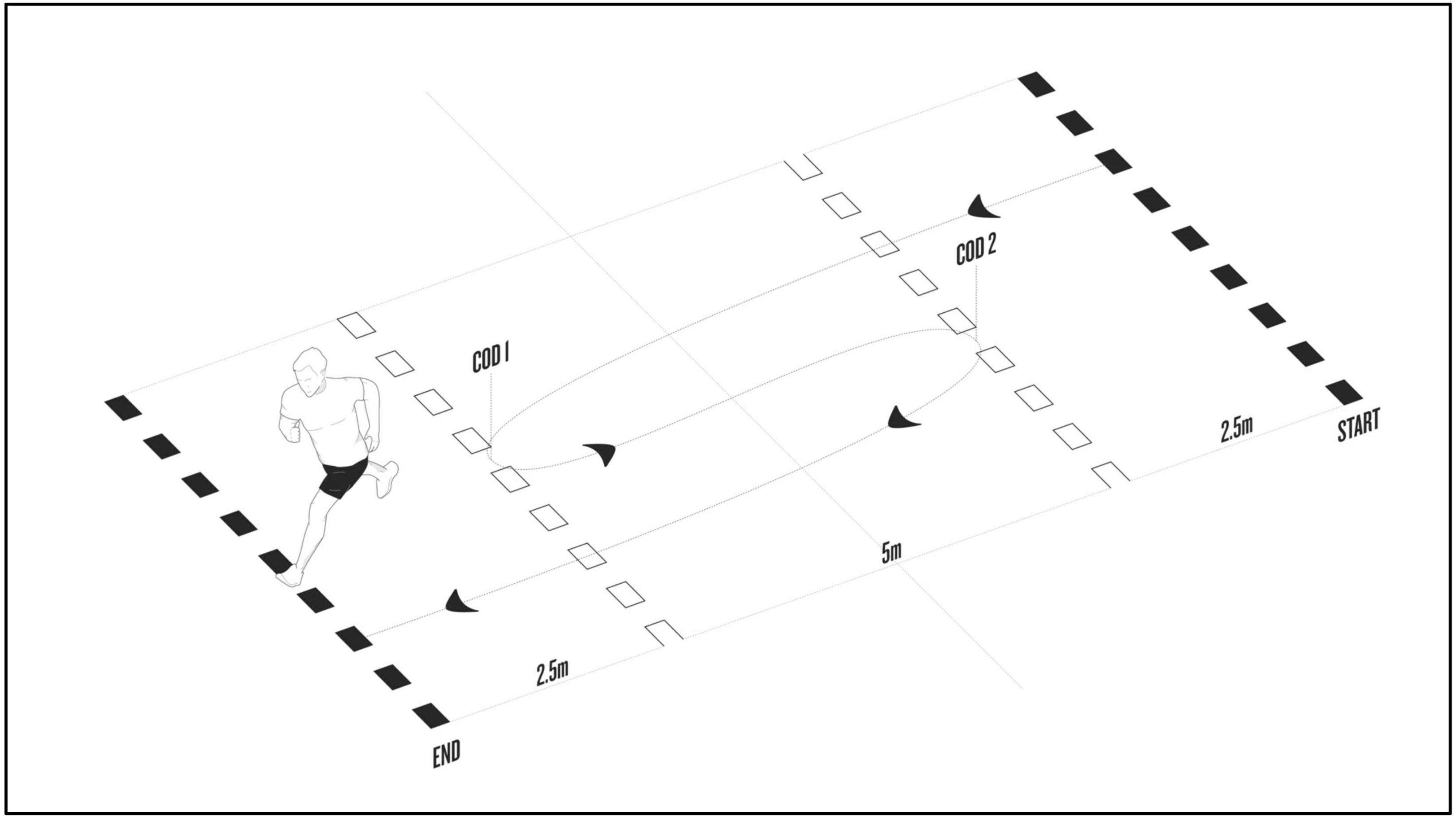

Figure 2. Schematic of the double 180º change of direction speed test (CODS180)

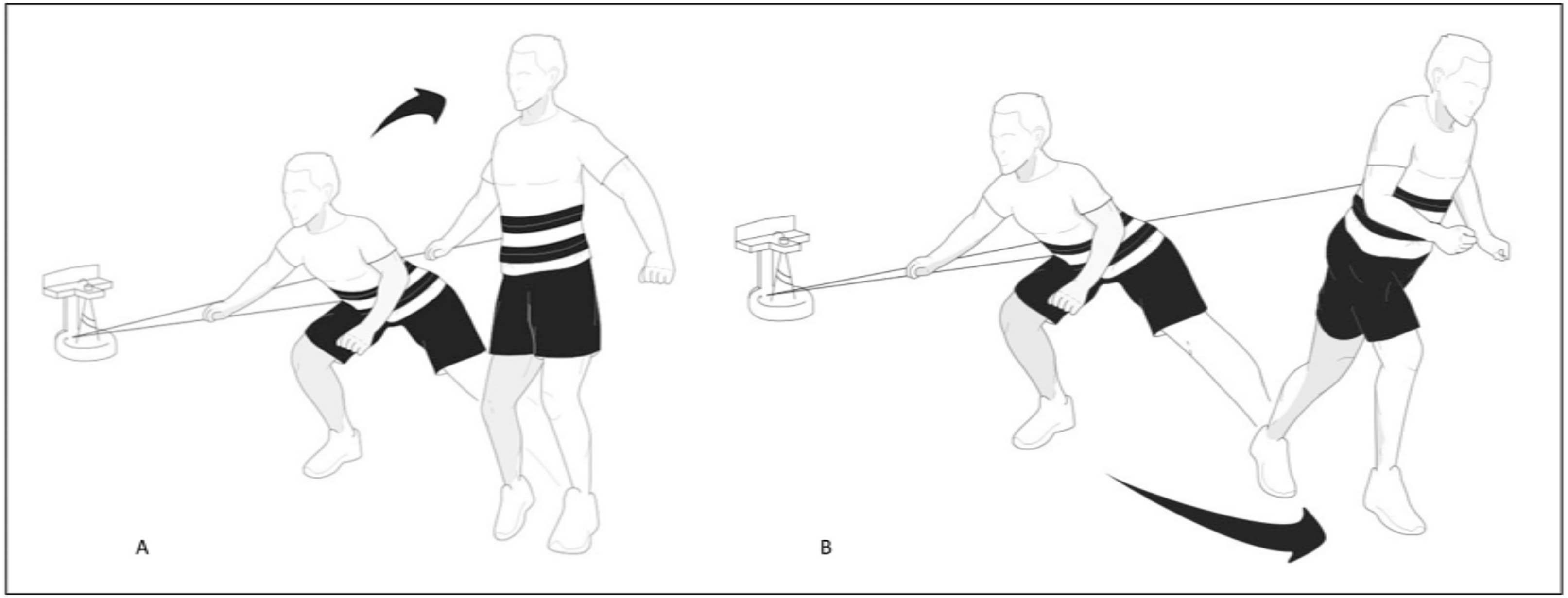

Figure 3. Testing conducted on the iso-inertial device. A = lateral shuffle step (LSS), phase start and brake; B = Crossover step (CRO), phase start and brake with the right leg.

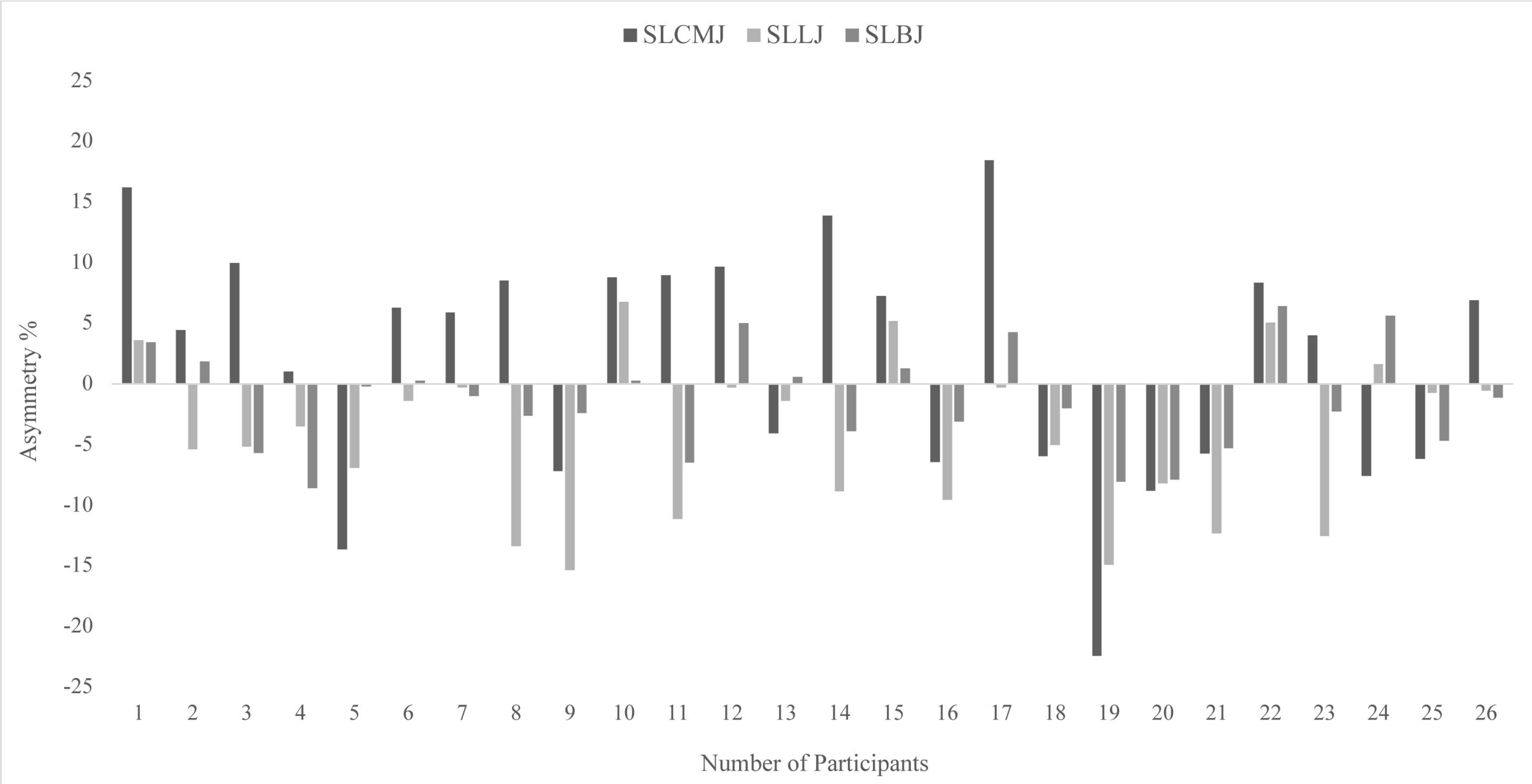

Figure 4. Individual asymmetry scores for the SLCMJ (jump height), SLLJ (distance) and SLBJ (distance) tests. Above 0 line means asymmetry favours the dominant leg and below 0 line means asymmetry favours the non-dominant limb.

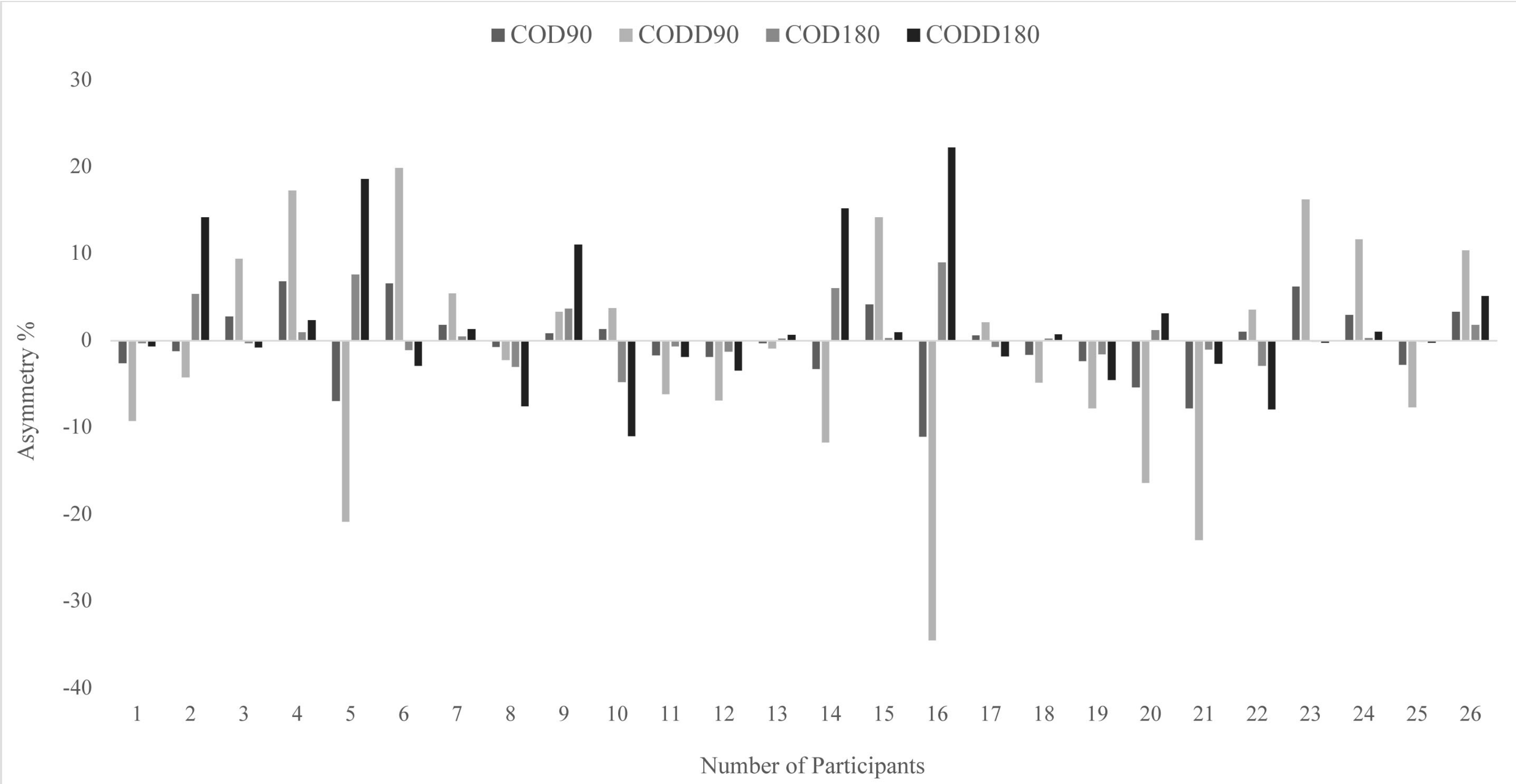

Figure 5. Individual asymmetry scores for the CODS90, CODD90, CODS180, CODD180 (time) tests. Above 0 line means asymmetry favours the dominant leg and below 0 line means asymmetry favours the non-dominant limb.

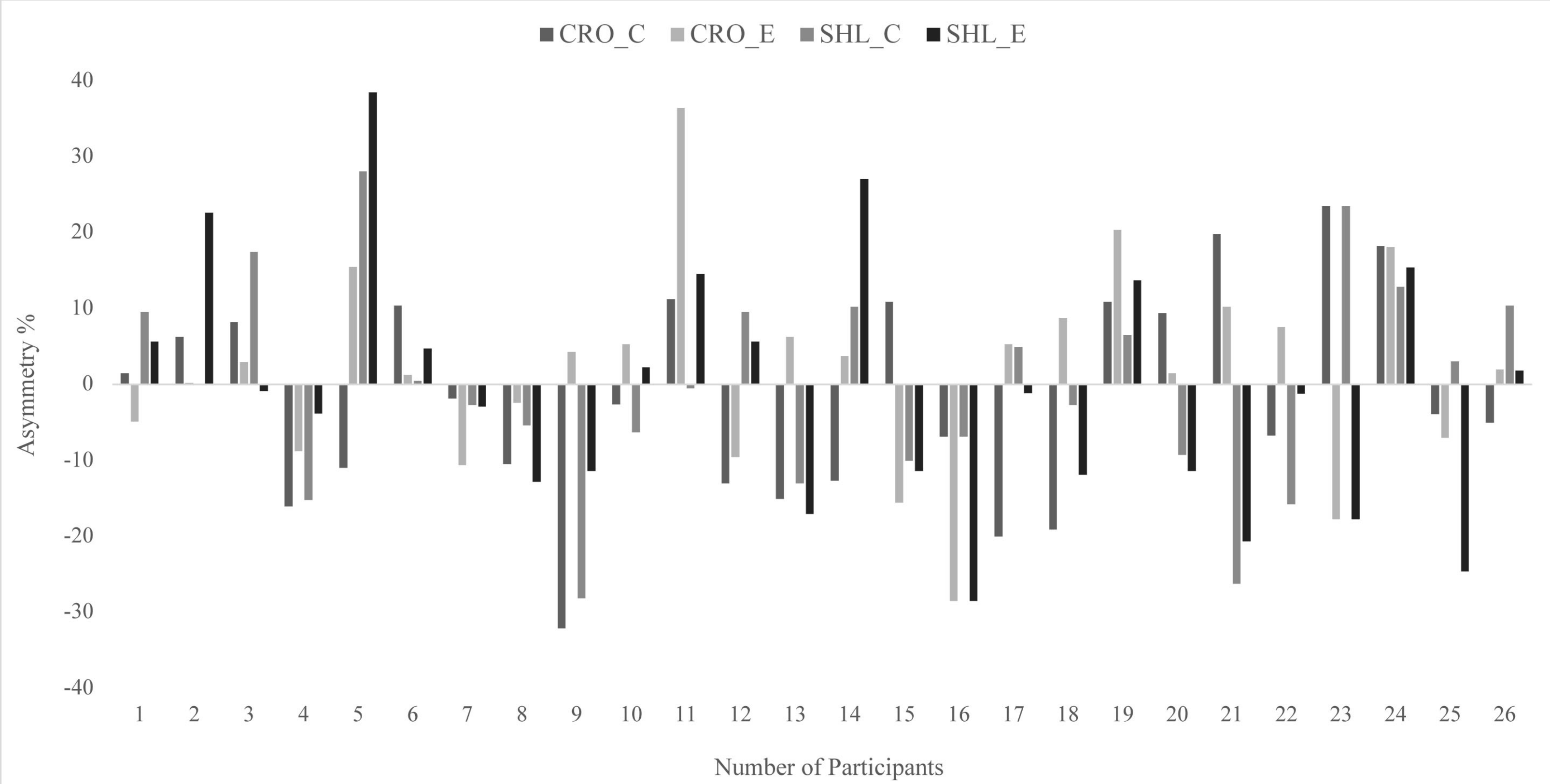

Figure 6. Individual asymmetry scores for the CRO_C, CRO_E, LSS_C, LSS_E (power) tests. Above 0 line means asymmetry favours the dominant leg and below 0 line means asymmetry favours the non-dominant limb.

STUDY 5

Effects of 8-weeks of Iso-inertial vs Cable-resistance Training on Motor Skills Performance and Inter-limb Asymmetry

Citation:

Madruga-Parera M, Bishop C, Beato M, Fort-Vanmeerhaeghe A, Gonzalo-Skok O, Romero-Rodriguez D. Effects of 8-weeks of Iso-inertial vs Cable-resistance Training on Motor Skills Performance and Inter-limb Asymmetry. J Strength Cond Res, **[Under review]**

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Journal of Strength and Conditioning Research; Impact factor: 3.017 (2019); Category: Sport Sciences; Quartile: Q1.

Abstract study 5

The aim of this study was to compare the effects of 8 weeks of iso-inertial vs. cable-resistance training on motor skills performance and inter-limb asymmetries in handball players. Thirty-four young male handball players (mean ± SD: age: 15.96 ± 1.39 years; height: 1.74 ± 0.73 m; body mass: 70.5 ± 13.3 kg) participated in a randomized trial. The players performed an iso-inertial program using a portable flywheel device or a cable-resistance device. Performance variations and inter-limb asymmetries in dominant (D) and non-dominant (ND) limb means of the unilateral countermovement jump (UCMJ), the unilateral lateral jump (ULJ), the unilateral broad jump (UBJ), handball throwing (HT), change of direction speed (COD180), the linear sprint (S20), the V-CUT test and the repeated change of direction (RCOD) were recorded. Significant interactions were shown in $RCOD_D$ (p = 0.003, η_p = 0.25), TH (p = 0.015, η_p = 0.17) and $UCMJ_{ASY}$ (p = 0.037, η_p = 0.13). Post-hoc testing revealed a higher effect sizes in the iso-inertial group ($p_{Bonferroni}$ < 0.05) for the performance improvements in $RCOD_D$ (-1.35 large vs -0.22, small) and HT (0.88, moderate vs 0.00, trivial), in addition to inter-limb asymmetry reductions in $UCMJ_{ASY}$ (-0.70 moderate vs -0.32, small). Significant main effects of time in COD180, RCOD, UCMJ and UBJ for both limbs (p < 0.05, from moderate to large effect size), and in ULJ_{ND} (p < 0.001, large), $UCMJ_{ASY}$ (p < 0.001, moderate), V-CUT (p = 0.014, small) and HT (p = 0.015, large) were found. The effect sizes revealed greater magnitudes in the iso-inertial group. In conclusion, although both resistance training programs improve players' performance of motor skills and reduce inter-limb asymmetries, greater improvements were recorded with the iso-inertial resistance training than with the cable-resistance methodology.

Key Words: Change of direction; jump; handball; young athletes.

INTRODUCTION

Handball is a high-intensity intermittent sport (19) characterized by repeated explosive actions such as jumping, change of direction (COD), accelerations, decelerations and ball throwing (28,37,45). The total distance covered in competitive matches has been shown to be ~3.231 m (30), with intensity variation occurring every 3.2 s (30). Averages of maximum speed (22 $km \cdot h^{-1}$) (1), accelerations (2.26 $acc \cdot min^{-1}$), decelerations (3.61 $dec \cdot min^{-1}$) and frequency of change of direction (7.88 $COD \cdot min^{-1}$) have also been described (23). Given the prevalence of COD actions in handball, it is unsurprising that this motor skills is considered to be of great relevance for the sport (30,37). The study of COD has previously focused on analyzing its association with eccentric muscle actions (6,7,22), braking strategies (34), the ability to change direction at different angles (9), and the capacity to perform COD actions repeatedly (6,33). However, information about the effects of resistance training programs on COD performance in handball athletes is scarce. In recent years, iso-inertial strength training has become a popular training method for developing strength to enhance sport-specific skills (14,24,36,43). Tesch et al. (42) suggested that one of the advantages of iso-inertial training is the increased effort required during both the concentric and eccentric phases of the exercise. Recently, Nuñez et al. (36) compared the effects of a 6-week unilateral lunge or bilateral squat iso-inertial program in team-sports players, showing how both methods improve the countermovement jump (CMJ) (d = 0.28-0.42) and COD speed performance in $COD90_D$ (d = 0.75-0.70). Similarly, Gonzalo-Skok et al. (14) used iso-inertial training to compare the effects of bilateral squats vs. multidirectional COD exercises in team-sports players, showing likely or very likely improvements in right-left legs in COD skills, in COD 10m (*d* = 0.61 - 0.54), COD 20m (*d* = 0.35 - 0.43), COD 25m (*d* = 0.26 - 0.37), and in jumping tests in CMJ (*d* = 0.42), unilateral countermovement jump (UCMJ) (*d* = 0.27 - 0.39), lateral jump (ULJ) (*d* = 0.51 - 0.87) and broad jump (UBJ) (*d* = 0.43 - 0.62). When considering the application of iso-inertial training, various authors have indicated that factors such as force vector application, variability and specificity to sporting movements are key aspects in optimizing transfer to sport (14,32,43).

However, traditional resistance training is still the most widespread strength training methodology, and has been designed with different levels of functionality, ranging from resistance machines and free weights to functional loading on cable machines (38,40). Many studies have shown the beneficial effects of traditional resistance training on jump (8,17,41), COD and speed performance (17,41). Hermassi et al. (17) used a combination of weightlifting and strength exercises (e.g., pull-over, snatches, bench press, clean and jerk) for 12 weeks in male handball players. The results showed the greatest improvements in CMJ (*d* = 2.59), squat jump (*d* = 1.54) and throwing velocity (*d* = 1.33 to 2.13). Additionally, in a 6-week weightlifting (hang power clean, power snatch, half squat) and vertical jump intervention, Teo et al. (41) showed the greatest improvements in CMJ (*d* = 0.70 - 0.34), squat jump (*d* = 0.85 - 0.39) and COD505 (*d* = 0.48 - 0.44) performance tests. While the benefits of strength and power training are irrefutable, the literature comparing free weight training and iso-inertial methods are scarce, and only two reviews have been published (27,44) with no definitive results in favor of either methodology.

In addition to performance, neuromuscular inter-limb asymmetries have frequently been studied to quantify performance differences between limbs (4,10,25). For example, Bishop et al. (4) showed that larger inter-limb asymmetries in the drop jump test (9.16%) are associated with slower performance during the COD505 test (r = 0.52 - 0.66) and 30m speed (r = 0.58) tests in adult female soccer players. Furthermore, Maloney et al. (26) recorded an association between drop jump asymmetries and slower COD90° times (r = 0.60) in healthy males. Madruga-Parera et al. (24) also related higher inter-limb asymmetries in the double COD test to decreased performance in UCMJ (r = 0.50 - 0.53) and COD actions (r = 0.50 - 0.63) in young elite tennis players. Despite these moderate associations, it is plausible to limit the possible cause and effect relationship of the aforementioned results.

Therefore, the aim of the current study was to evaluate the effects of 8 weeks of a resistance training program based on COD exercises using either iso-inertial resistance or cable-resistance training devices, on motor skills performance and inter-limb asymmetries. The authors hypothesized that both training types could be effective to improve motor skills values in handball players, although iso-inertial training would be more effective than cable-resistance training.

Methods

Experimental approach to the problem

This research used a randomized trial to determine the effect of strength training on motor skills variables in young handball players. For the purpose of ensuring that the maturity state of the subjects was not an influential factor in the results, peak height velocity (PHV) was calculated following the formula proposed by Mirwald et al. (31), where early maturing (pre-PHV) is defined as preceding the average age of PHV by 1 year, average maturing (circa-PHV) refers to ± 1 year from PHV, and late maturing means > 1 year after PHV (post-PHV). All the athletes were previously familiarized with the testing procedures. The tests included bilateral and unilateral jumps, COD sprints over several distances, linear sprint and a throwing handball test. Furthermore, asymmetries were calculated in all the unilateral tests. Testing sessions were separated by a 48-hour recovery period (Figure 1). To record the different tests, the evaluators were blinded and the players were asked not to perform any strenuous exercise the day before each test, to consume their last meal at least 3 hours before the scheduled tests, and to avoid caffeine supplements for at least 24 hours before the tests.

** PLEASE INSERT FIGURE 1 ABOUT HERE **

Subjects

Thirty-four young male handball players (mean ± SD: age: 15.96 ± 1.39 years; post-peak high velocity: 1.42 ± 1.39; height: 1.74 ± 0.73 m; body mass: 70.5 ± 13.3 kg) volunteered to participate in this study. Data collection took place during the competitive season after a 2-month pre-season period. All the players were actively involved in a high-level young handball league, doing three training sessions (approximately 4.5 hours) and playing a competitive match per week. Subjects were eligible for inclusion if they had > 4 years of competitive handball experience and were excluded if they presented an injury (overuse or acute) at the time of testing. Before taking part in the study, participants and their parents/guardians were fully informed about the protocol and provided their written informed consent. The Catalan Sports Council Ethics Committee approved the procedures in accordance with the latest version of the Declaration of Helsinki.

Procedures

The tests were performed in two different sessions. Jumping and throwing tests were administered on the first day, while linear sprint and COD tests were carried out on the second day. A standardized warm-up was performed prior to the tests, consisting of five minutes of light jogging, three minutes of dynamic stretches and five minutes of lower body strength work such as multi-directional lunges, inchworms, bodyweight squats and planks. Upon completion, three practice trials were provided for each test where subjects were instructed to perform them at 75, 90 and 100% of their perceived maximal effort. Three minutes rest was given between the last practice trial and the start of the tests, which were administered in a randomized order.

Day 1. Unilateral countermovement jump (UCMJ) This test was performed on a contact mat (Chronojump, Boscosystem, Barcelona Spain), and jump height was measured. Subjects were required to step onto the center of the contact mat with one leg and place their hands on their hips. When ready, they performed a countermovement to a self-selected depth before accelerating as forcefully as possible into a unilateral vertical jump, following the instructions to 'jump as high as you can'. The non-jumping leg was slightly flexed at the knee with the foot hovering next to the ankle of the jumping leg. No additional swinging of the non-jumping leg was allowed during the jump and hands were required to remain fixed at the hips. Any deviations from these criteria resulted in a void trial and the test was subsequently retaken. Three trials were performed on each leg with 60 seconds rest given between each trial. The highest jump on each leg was then used for subsequent data analysis (12,24,29).

Unilateral lateral jump (ULJ) This test was performed to measure lateral jump distance using a standard measuring tape fixed to the floor. The subjects started just behind 0 cm with the selected test leg, performing a countermovement to a self-selected depth before jumping laterally as far as possible in the direction of the tape measure (without landing directly on it), with hands placed and held on the hips throughout. Considering the difficulty of this test, the landing was performed on both limbs to increase the chance of a stable landing. The subjects were required to maintain the landing position for 2 seconds. The jumping distance was measured from the heel of the jumping foot. Three trials were performed on each leg with 60 seconds rest given between each trial. The trial with the furthest jump on each leg was then used for subsequent data analysis (12,24,29).

Unilateral broad jump (UBJ). This test was performed to measure horizontal jump distance (in cm) using a standard measuring tape fixed to the floor. The subjects started with their toes just behind 0 cm with the selected test leg, performing a countermovement to a self-selected depth before jumping forward as far as possible along the direction of the tape measure (without landing directly on it), with hands placed on the hips throughout. The subjects were required to maintain the landing position for 2 seconds. The jumping distance was measured from the heel of the jumping foot. The non-jumping leg was slightly flexed at the knee with the foot hovering next to the ankle of the jumping leg. No additional swinging of the non-jumping leg was allowed during the jump. Any deviations from these criteria resulted in a void trial and the test was subsequently retaken. Three trials were performed on each leg with 60 seconds rest given between each trial. The furthest jump on each leg was then used for data analysis (12,24,29).

Handball Throwing test (HT). Subjects were required to stand on a throwing point 7 m from the goal (penalty line). The procedure proposed by Saeterbakken et al. (39) was to perform a maximum throwing action with the ball (mass 480 g and circumference 58 cm). The ball velocity was determined by using speed radar (16-177 $km \cdot h^{-1}$; 27 m; Bushnell Speedster II; USA). The radar was placed behind the goal. Three trials were performed with 120 seconds rest given between each trial. The quickest throw was then used for subsequent data analysis.

Change of Direction 180° Speed test (COD180). Subjects performed two 180° changes of direction using the same leg in each trial for both the dominant (COD180_D) and the non-dominant (COD180_ND) legs (24). The first change of direction was performed 7.5 m after the start, and the second one was performed 5 m after the first change of direction. The subjects sprinted for a distance of 20 m. Total time in the COD test was measured using photocell beams (Chronojump Boscosystem, Barcelona, Spain) placed at a height of 0.75 m (in all the speed tests). The fastest time of the three trials for each leg was used for the analysis. A trial was considered successful if the entire foot crossed over the line while changing direction. Each trial was separated by a 180-second recovery period. An adapted calculation was used to evaluate the COD deficit, as described by Nimphius et al. (35). Thus, the COD deficit was calculated as follows: S20 velocity-COD test velocity.

Linear sprint 20 m (S20). Time in the sprint test was measured using photocell beams placed on the starting line and after 20 m. The photocells were connected to a laptop and analyzed using a software (Chronojump, BoscoSystem, Barcelona, Spain). The front foot was placed 0.5 m in front of the first photocell beams. The fastest time of the three trials was used for the analysis. Each trial was separated by a 180-second recovery period.

V-CUT test. Subjects performed a 25 m circuit at maximum speed, with four 45° COD actions, each one after a distance of 5 m (13). To achieve a valid trial, the subjects had to pass the line clearly marked on the floor with each respective foot at every turn. The distance between each pair of cones was 0.7 m. The photocells were connected to a laptop and analyzed using a software (Chronojump, BoscoSystem, Barcelona, Spain). Three trials were performed with 180 seconds rest provided between each and the fastest trial was subsequently used for further analysis.

<u>*Repeated change of direction (RCOD) 8 x 10 m*</u>. This test is related to the athlete's capacity to resist fatigue during a change of direction task. The test involved eight continuous repetitions of a 10 m sprint, with each 10 m sprint requiring a 180º change of direction at the halfway point (5 m). A photocell beam sensor was connected to Chronojump software to acquire the data (Chronojump BoscoSystem, Barcelona, Spain). For the purpose of observing the association between inter-limb asymmetries and performance when athletes are in an acute state of 'fatigue', we modified this previously validated CODS test (5) by carrying out 8 consecutive sprints (no rest between any of them), instead of a single maximal effort. Owing to the fact this test acutely induces fatigue it was only performed twice, ensuring each time that all the turns were conducted off the same limb. A rest period of 5 minutes between trials was provided, with the outcome of total time for all 8 sprints combined and used for further analysis.

Training intervention

Players from the same handball club were assigned to either an iso-inertial (n = 17) or a cable (n = 17) resistance training program. A portable iso-inertial device (Byomedic System^{SCP}, Barcelona, Spain) (32) was used in the iso-inertial program. The cable-resistance group used a cable-resistance machine (Salter Sport SA, Functional trainer Inspire FT1, Barcelona, Spain) (Figure 2).

** PLEASE INSERT FIGURE 2 ABOUT HERE **

The resistance training program lasted 8 weeks (Table 1) and consisted in two weekly sessions that including COD ability, perception constraints and specific handball skills (Figure 3). The progression of this program was focused on the introduction of new skills and specific constraints every two weeks (more steps to develop the actions, increased planes of motion and the introduction of a number of specific skills). The load (inertia and weight) was adapted to the subjects in each session using the Scale of Rate of Perceived Effort (RPE), as suggested in previous studies (16). The players were encouraged to perform the different exercises at maximum effort. Two qualified strength and conditioning coaches controlled each training session, providing the subjects with verbal encouragement and specific coordinative feedback (e.g. “keep down the center of gravity”, “stabilize the core and lower limbs at the braking stage”, “accelerate as fast as you can”).

This strength program was added to the subjects’ regular handball training (three 90-minutes sessions per week on Monday, Wednesday and Friday) and a competitive match over the weekend. The handball training included technical and tactical skills and excluded any other strength program.

** PLEASE INSERT TABLE 1 & FIGURE 3 ABOUT HERE **

Statistical analysis

The data are presented in mean ± standard deviation (SD). The assumption of normality was verified using the Shapiro-Wilk test and the Q-Q plots and histogram of residuals were explored. An intra-day reliability test was performed and interpreted in line with Koo and Li (20), where values > 0.9 = *excellent*, 0.75 - 0.9 = *good*, 0.5 - 0.75 = *moderate* and < 0.5 = poor. The effectiveness of the interventions was assessed by a 2-way mixed ANOVA. Group intervention ("ISO", "Cable") was included as a between-subject factor; time ("Pre", "Post") was included as the repeated within-subject factor; and group x time was included to account for the interaction effects. Whenever a significant mean effect or interaction was observed, Bonferroni's post hoc correction was used to aid interpretation of these interactions. Within-subject Cohen's effect size was calculated using the formula $d = t/\sqrt{(n)}$ (21) and was interpreted as < 0.2 = *trivial*; 0.2-0.6 = *small*; 0.6-1.2 = *moderate*; 1.2-2.0 = *large*; > 2.0 = *very large* (18). Researchers were blind to all subjects during the analyses. The significance level was set at ⍰ = 0.05 for all the tests. All the statistical analyses were performed in JASP (version 0.11.1; JASP Team, 2019, University of Amsterdam, the Netherlands).

Inter-limb asymmetries were calculated for all tasks, defining the dominant (D) (the limb with the better score) and the non-dominant (ND) limbs. The mean inter-limb asymmetries were computed using a standard percentage difference equation: 100/(max value)*(min value)*-1*100, which is an accurate equation for the quantification of asymmetries in unilateral tests (3).

RESULTS

<u>Participants</u>

Only players who participated in at least 80% of the training sessions were analyzed. Consequently, 6 of the forty players were excluded for various reasons. None of the players were injured during the resistance training sessions. As a result, 34 players (mean ± SD: age: 15.96 ± 1.39 years; post-peak high velocity: 1.42 ± 1.39; height: 1.74 ± 0.73 m; body mass: 70.5 ± 13.3 kg) were included in the final analyses. Furthermore, for 28 out of the 34 players their preferred leg (i.e., kicking leg) was the right leg, and 31 right of the 34 players preferred the right arm (i.e., throwing arm). The final sample sizes for the training groups were 17 for the iso-inertial group and 17 for the cable-resistance group.

Tests' reliability

Intra-day reliability in pre- and post-intervention tests was *good* to *excellent* (Table 2).

Effectiveness of intervention groups

The summary of the results for change of direction and linear sprint are shown in Table 3.

** PLEASE INSERT TABLE 2 & 3 ABOUT HERE **

180° Change of Direction Speed test

The data revealed a significant main effect of time ($p < 0.001$) in changes of direction performed with both the dominant (d = -0.83, moderate) and the non-dominant legs (d = -0.71, moderate). However, non-significant interactions were shown in both legs (D: $p > 0.05$, η_p = 0.00; ND: $p > 0.05$, η_p = 0.00), indicating a similar improvement in both groups. A non-significant main effect of time and interaction were observed in the asymmetry index (time: p = 0.570, d = 0.10, trivial; group*time: p = 0.480, η_p = 0.02) in change of direction and in change of direction deficit (time: p = 0.356, d = 0.10, trivial; group*time: p = 0.314, η_p = 0.01).

V-CUT test

The data revealed a significant main effect of time (p = 0.014, d = -0.43, small) and a non-significant interaction (p = 0.092, η_p = 0.09) in the V-Cut test, indicating that a similar improvement occurred in both groups.

Repeated change of direction 8 x 10 m

The data revealed a significant main effect of time ($p < 0.001$) in repeated changes of direction performed with both the dominant (d = -0.69, moderate) and the non-dominant legs (d = -0.71, moderate), while a non-significant main effect of time was observed in the asymmetry index (p = 0.303, d = -0.19, trivial). Significant interactions were shown in repeated changes of direction performed with the dominant leg (p = 0.003, η_p = 0.25) only. The post-hoc test showed a significant difference between “Pre” (15.96 ± 2.00) and “Post” (12.59 ± 1.50) in the iso-inertial group ($p_{Bonferroni} \leq 0.05$, d = -1.35, large), indicating that an improvement occurred in this group only.

Linear sprint 20 m (S20)

The data revealed a non-significant main effect of time (p = 0.866, d = -0.03, trivial) and interaction (p = 0.119, η_p = 0.07) in the 20 m-sprint time.

The summary of the results in the jump and handball throwing tests are shown in Table 4.

** PLEASE INSERT TABLE 4 ABOUT HERE **

Unilateral countermovement jumps

The data revealed a significant main effect of time ($p < 0.001$) in jumps performed with both the dominant ($d = 0.93$, moderate) and the non-dominant legs ($d = 1.06$, moderate) and in the asymmetry index ($d = -0.66$, moderate). Significant interaction was revealed in the asymmetry index ($p = 0.037$, $\eta_p = 0.13$). The post-hoc test showed a significant difference between "Pre" (14.81 ± 8.82) and "Post" (6.05 ± 2.93) in the iso-inertial group ($p_{Bonferroni} \leq 0.05$, $d = -0.70$, moderate), indicating that an improvement occurred in this group only.

Unilateral lateral jumps

The data only revealed a significant main effect of time in the unilateral lateral jumps performed with the non-dominant leg ($p = 0.022$, $d = 0.42$, small).

Unilateral broad jump.

The data revealed a significant main effect of time ($p < 0.001$) in the unilateral broad jumps performed with both the dominant ($d = 1.37$, large) and the non-dominant leg ($d = 1.20$, large), while the main effect in the asymmetry index was not significant ($p = 0.427$, $d = -0.12$, trivial). Non-significant interactions were revealed in both the dominant ($p = 0.126$, $\eta_p = 0.07$) and the non-dominant ($p = 0.876$, $\eta_p = 0.00$) unilateral broad jumps and in the asymmetry index (($p = 0.121$, $\eta_p = 0.07$)), indicating a similar evolution in the two groups.

Handball throwing test

The data revealed a significant main effect of time (p = 0.015, d = 0.41) and interaction (p = 0.015, η_p = 0.17) in the handball throwing test. The post-hoc test showed a significant difference between "Pre" (70.76 ± 1.18) and "Post" (72.94 ± 7.33) in the iso-inertial group ($p_{Bonferroni} \leq 0.05$, d = 0.88, moderate), indicating that an improvement occurred in this group only.

DISCUSSION

The aim of the current study was to evaluate the effects of an 8-week resistance-training program based on COD exercises using either iso-inertial or cable-resistance devices. Motor skills performance and inter-limb asymmetries were recorded in a wide range of tests such as COD, sprinting, jumping and throwing actions. Both resistance training programs showed improvements in the motor skills variables. When comparing groups, significant results were found in favor of the iso-inertial training in $RCOD_{DL}$ and HT performance, as well as for UCMJ inter-limb asymmetries. Furthermore, the iso-inertial resistance group showed greater non-significant training effects in COD180, $RCOD_{ND}$, V-CUT, UCMJ, ULJ and UBJ. Meanwhile, the cable-resistance group showed greater non-significant training effects in COD180, $RCOD_{ND}$ and UBJ_{ND}.

Given the importance of COD actions in handball (30,37), we developed three COD tests with different specifications: COD180, V-CUT and RCOD. The COD180 showed positive effects in both training methods, with superior improvements on comparing with previous data with team sport players (d = -

0.28 and -0.61 for D and ND, respectively) (14). Considering the improvement in both groups, highlighting the design of our intervention over the applied resistance kind makes sense. Regarding the V-CUT test, moderate effects were obtained only in the iso-inertial group, being in agreement with Tous-Fajardo et al. (43), who registered better times in the V-CUT test after an iso-inertial resistance training program with multidirectional COD in young soccer players. It is important to emphasize these results, taking the multidirectional nature of this test and its relationship with the demands of the change of direction in handball into account. It is plausible to think that the nature of the iso-inertial resistance intervention, which is focused on the concentric and eccentric actions (11) and accentuates the required effort of the breaking phases (42), could bring about these adaptations. These events could explain the aforementioned adaptations. Concerning the $RCOD_D$ test, significant improvements were reported in the iso-inertial group, while moderate effects were found in $RCOD_{ND}$ in both groups. Such improvements agree with Tous-Fajardo et al. (43), who analyzed the effects on repeated sprint ability with young football players following an iso-inertial training. Considering these results, it is important to highlight the great adaptation to repetitive stimulus showed by both training groups, although superior results were again found after the iso-inertial training. In contrast to the positive results showed in COD actions, no favorable within-group and between-group effects were shown in the 20 m sprint test, with similar results to Tous-Fajardo et al. (43) in the 10 m and 30 m sprint distances, confirming the lack of transfer from our COD-task intervention to linear skills.

Regarding asymmetries, the present research did not show any effect in the COD tests. Given that the available literature is not reporting a cause and effect relationship between performance improvement and reduction of inter-limb asymmetries, the positive effects of the present intervention on performance without achieving any decrease of COD asymmetries can be accepted.

In jumping tests, greater effects were found in UCMJ, ULJ_{ND} and UBJ for the iso-inertial group, while only UBJ showed improvements in the cable-resistance group. This is a significant finding since jump capacity is an important specific skill in handball (15). The improvement in jumping capability after an iso-inertial resistance training program has been previously shown by Gonzalo-Skok et al. (14) in UCMJ (*d* = 0.27 and 0.39, for D and ND, respectively) and the single-hop test (*d* = 0.43 and 0.62, for D and ND, respectively). The positive effects on jumping performance after iso-inertial training is an interesting point to consider, especially given that this intervention program was non-focused on this motor skills but nonetheless reported a transfer effect.

Related to jumping asymmetries, between-group differences in favor of the iso-inertial training group were limited to UCMJ, while non-differences were reported in ULJ and UBJ. Our results contrast with the previous literature, which has showed asymmetries reductions in single and triple hop tests (12) with iso-inertial resistance training. These divergent data related to the direction of jumping action undergoing a decrease in asymmetry suggest the need to increase the number of experimental designs to determine a more consistent adaptation in jumping asymmetry after iso-inertial strength training. Nevertheless, with respect to the asymmetry reduction in UCJMJ, the present program, which included a wide range of unilateral coordinative tasks, gave a positive adaptation since high scores in vertical jumping asymmetries were related to a decrease in sprint and COD performance (2,24).

To complete the performance screening of the present study, a handball throwing speed test was performed, reporting differences between groups in favor of iso-inertial training. Previous studies have related the transfer of forces from core muscles to the upper limbs and throwing performance after traditional abdominal training (39) and upper limb weightlifting exercises (17). Considering these studies and the continued presence of trunk rotational movements through the present strength program, it is plausible to understand the throwing speed gain by means of the existence of a kinetic chain working from the lower to the upper limbs, especially when there is a high demanding eccentric overload produced by the iso-inertial devices.

There are two methodological considerations related to the present study. First, despite being focused on sport specific skills, the developed program is still removed from the competitive environment, so the adaptations are related to the effects of motor skills tests but not to sport performance. Second, and related to the actions carried out by the volunteers throughout the initial phase of the present study, when working with iso-inertial resistance, which is still little used by athletes, more thorough familiarization with this type of training is recommended before starting an experimental intervention.

Practical Applications

This study supports the introduction of the iso-inertial methodology when applying strength resistance training in order to improve motor skills performance. Practitioners can thereby introduce a strength program based on motor skills and perceptual constraints, increasing the coordinative difficulty without limiting any positive adaptations and facilitating the reduction of inter-limb asymmetries.

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TABLES AND FIGURES
STUDY 5

Table 1. Programme training, exercises, stimuli and load following iso-inertial and cable resistance groups

Stage	Week	Exercise	Purpose of exercise	Load sets & reps	RPE
1	1-2	Forward lunge	Ball in the hands	3x12	6-7
	1-2	Acceleration	1 step – ball in the hands	3x12	6-7
	1-2	Lateral squat	Ball in the hands	3x12	6-7
2	3-4	Single leg hop	Simulating passes	3x12	7-8
	3-4	Acceleration	2 steps – simulating passes	3x12	7-8
	3-4	Lateral lunge	Simulating passes	3x12	7-8
3	5-6	Crossover step	Simulating passes	3x8	8-9
	5-6	Acceleration	2 steps – pass and receive	3x8	8-9
	5-6	Lateral step & UCMJ	Simulating passes	3x8	8-9
4	7-8	Crossover step	Pass and receive	3x8	8-9
	7-8	Acceleration	2 steps – defense action	3x8	8-9
	7-8	180º turn	Pass and receive	3x8	8-9

Reps: repetitions; RPE: scale rated of perceived effort; UCMJ: unilateral countermovement jump

Table 2. Intra-day intraclass correlation coefficient reliability, following baseline tests.

PRE-TEST RELIABILITY (n = 34)				
Test	**TRIAL 1**	**TRIAL 2**	**CV (%)**	**ICC (95% CI)**
$COD180_R$ (s)	5.41 ± 0.55	5.36 ± 0.54	1.8	0.97 (0.95 to 0.98)
$COD180_L$ (s)	5.44± 0.55	5.40 ± 0.57	2.1	0.97 (0.94 to 0.98)
V-CUT (s)	7.36 ± 0.67	7.29 ± 0.64	1.5	0.97 (0.95 to 0.98)
$RCOD_R$ (s)	15.82 ± 2.20	15.86 ± 2.11	1.3	0.94 (0.92 to 0.96)
$RCOD_L$ (s)	15.72 ± 2.01	15.26 ± 2.01	2.1	0.95 (0.90, 0.97)
S20 (s)	3.20 ± 0.29	3.18 ± 0.32	1.3	0.98 (0.97 to 0.99)
$UCMJ_R$ (cm)	13.73 ± 3.63	13.73 ± 3.64	6.7	0.95 (0.90 to 0.97)
$UCMJ_L$ (cm)	13.12 ± 3.66	12.82 ± 3.51	8.5	0.91 (0.83 to 0.96)
ULJ_R (cm)	122.93 ± 23.14	124.35 ± 23.83	5.8	0.92 (0.84 to 0.96)
ULJ_L (cm)	128.94 ± 20.80	133.43 ± 20.32	4.1	0.95 (0.91 to 0.97)
UBJ_R (cm)	121.81 ± 21.57	126.78 ± 21.48	5.6	0.91 (0.82 to 0.95)
UBJ_L (cm)	121.79 ± 22.08	127.20 ± 26.45	5.4	0.94 (0.88 to 0.97)
HT ($km \cdot h^{-1}$)	66.50 ± 6.17	68.32 ± 6.49	3.3	0.93 (0.86 to 0.98)

Data are means ± SD; CV = coefficient of variation; ICC = intraclass correlation coefficient; CI = confidence intervals; cm: centimeters; s: seconds; R: right leg; L: left leg; COD: change of direction speed; V-Cut: multidirectional change of direction; RCOD: repeated change of direction 10x8; S20: 20 meters linear sprint test; UCMJ: unilateral countermovement jump; ULJ: unilateral lateral jump; UBJ: unilateral broad jump; HT: handball throwing test.

Table 3. Summary of study results

Outcome	Group	Pre	Post	Cohen's *d*	*p* (Time)	*p* (Group)	*p* (Time*group)
$COD180_D$ (s)	All	5.26 ± 0.53	5.08 ± 0.42	-0.83	<0.001	0.644	0.931
	Iso-inertial	5.22 ± 0.36	5.04 ± 0.36	-0.83			
	Cable resistance	5.30 ± 0.58	5.12 ± 0.48	-0.80			
$COD180_{ND}$ (s)	All	5.39 ± 0.54	5.23 ± 0.48	-0.71	<0.001	0.528	0.744
	Iso-inertial	5.33 ± 0.50	5.18 ± 0.43	-0.65			
	Cable resistance	5.45 ± 0.59	5.28 ± 0.54	-0.76			
$COD180_{ASY}$ (%)	All	2.42 ± 2.04	2.66 ± 1.88	0.10	0.570	0.251	0.480
	Iso-inertial	1.96 ± 1.81	2.51 ± 1.56	0.16			
	Cable resistance	2.88 ± 2.21	2.82 ± 2.19	-0.02			
$CODD180_{ASY}$ (%)	All	5.77 ± 4.81	6.77 ± 4.84	0.10	0.356	0.262	0.314
	Iso-inertial	4.75 ± 4.31	6.34 ± 4.05	0.22			
	Cable resistance	6.80 ± 5.19	7.19 ± 5.61	-0.02			
V-CUT (s)	All	7.25 ± 0.65	7.15 ± 0.61	-0.43	0.014	0.688	0.092
	Iso-inertial	7.24 ± 0.62	7.07 ± 0.54	-0.74			
	Cable resistance	7.26 ± 0.70	7.23 ± 0.68	-0.15			
$RCOD_D$ (s)	All	15.26 ± 2.02	13.31 ± 2.51	-0.69	<0.001	0.968	0.002
	Iso-inertial	15.96 ± 2.00	12.59 ± 1.50*	-1.35			
	Cable resistance	14.57 ± 1.84	14.02 ± 3.11	-0.22			
$RCOD_{ND}$ (s)	All	16.28 ± 2.08	14.00 ± 2.68	-0.71	<0.001	0.528	0.744
	Iso-inertial	16.87 ± 2.25	13.11 ± 1.73	-0.65			
	Cable resistance	15.69 ± 1.77	14.89 ± 3.20	-0.76			
$RCOD_{ASY}$ (%)	All	6.08 ± 6.25	4.88 ± 2.74	-0.19	0.303	0.103	0.948
	Iso-inertial	5.13 ± 5.77	3.86 ± 2.64	-0.17			
	Cable resistance	7.03 ± 6.73	5.91 ± 2.50	-0.14			
S20 (s)	All	3.16 ± 0.30	3.16 ± 0.33	-0.03	0.866	0.740	0.119
	Iso-inertial	3.16 ± 0.32	3.12 ± 0.30	-0.30			
	Cable resistance	3.16 ± 0.29	3.19 ± 0.37	0.24			

Data are presented as mean ± SD. D: dominant leg; ND: non-dominant leg; cm: centimeters; s: seconds; ASY: inter-limb asymmetries; COD180: 180° change of direction; V-CUT: multidirectional change of direction test; RCOD: repeated change of direction 8x10; S20: linear sprint 20 m.
Significant Cohen's *d* and *p*-values ($p \leq 0.05$) are shown in bold.
* $p_{Bonferroni} \leq 0.05$ different to baseline values.

Table 4. Summary of study results

Outcome	Group	Pre	Post	Cohen's *d*	*p* (Time)	*p* (Group)	*p* (Time*group)
$UCMJ_D$ (cm)	All	15.34 ± 3.65	18.20 ± 3.67	0.93	<0.001	0.248	0.272
	Iso-inertial	15.71 ± 4.19	19.15 ± 3.72	1.12			
	Cable resistance	14.97 ± 3.09	17.24 ± 3.45	0.74			
$UCMJ_{ND}$ (cm)	All	13.48 ± 3.36	17.00 ± 3.40	1.06	<0.001	0.386	0.072
	Iso-inertial	13.41 ± 3.77	17.96 ± 3.40	1.41			
	Cable resistance	13.55 ± 3.77	16.05 ± 3.22	0.78			
$UCMJ_{ASY}$ (%)	All	12.12 ± 8.58	6.42 ± 3.36	-0.66	<0.001	0.172	0.037
	Iso-inertial	14.81 ± 8.82	6.05 ± 2.93*	-0.70			
	Cable resistance	9.44 ± 7.66	6.79 ± 3.80	-0.32			
ULJ_D (cm)	All	139.17 ± 19.58	143.34 ± 19.33	0.30	0.096	0.164	0.764
	Iso-inertial	143.91 ±18.59	147.34 ± 21.43	0.24			
	Cable resistance	134.44 ± 19.53	139.35 ± 16.67	0.35			
ULJ_{ND} (cm)	All	128.42 ± 21.84	133.95 ± 20.06	0.42	0.022	0.133	0.669
	Iso-inertial	133.60 ± 20.63	139.60 ± 20.52	0.49			
	Cable resistance	123.77 ± 22.64	128.31 ± 18.47	0.34			
ULJ_{ASY} (%)	All	7.86 ± 7.94	6.71 ± 4.80	-0.18	0.315	0.374	0.330
	Iso-inertial	7.55 ± 7.38	5.27 ± 3.53	-0.34			
	Cable resistance	8.18 ± 8.69	8.15 ± 5.53	-0.00			
UBJ_D (cm)	All	138.48 ± 23.22	155.93 ± 21.48	1.37	<0.001	0.746	0.126
	Iso-inertial	138.02. ± 23.51	158.82 ± 24.07	1.67			
	Cable resistance	138.94 ± 23.63	153.04 ± 18.82	1.13			
UBJ_{ND} (cm)	All	128.68 ± 21.37	146.21 ± 20.06	1.20	<0.001	0.783	0.876
	Iso-inertial	129.81 ± 24.07	146.94 ± 20.70	1.15			
	Cable resistance	127.54 ± 19.87	145.47 ± 20.00	1.21			
UBJ_{ASY} (%)	All	6.97 ± 4.71	6.05 ± 5.10	-0.12	0.427	0.987	0.121
	Iso-inertial	5.97 ± 5.29	7.07 ± 5.84	0.15			
	Cable resistance	7.97 ± 3.95	5.03 ± 4.16	-0.40			
HT ($km \cdot h^{-1}$)	All	69.82 ± 6.60	70.91 ± 6.50	0.41	0.015	0.181	0.015
	Iso-inertial	70.76 ± 1.18	72.94 ± 7.33*	0.88			
	Cable resistance	68.88 ± 6.04	68.88 ± 4.97	0.00			

Data are presented as mean ± SD. D: dominant leg; ND: non-dominant leg; cm: centimeters; s: seconds; ASY: inter-limb asymmetries; UCMJ: Unilateral countermovement jump; ULJ: Unilateral lateral; UBJ: Unilateral broad jump; HT: Handball throwing test. Significant Cohen's *d* and *p*-values ($p \leq 0.05$) are shown in bold.

* $p_{Bonferroni} \leq 0.05$ different to baseline values.

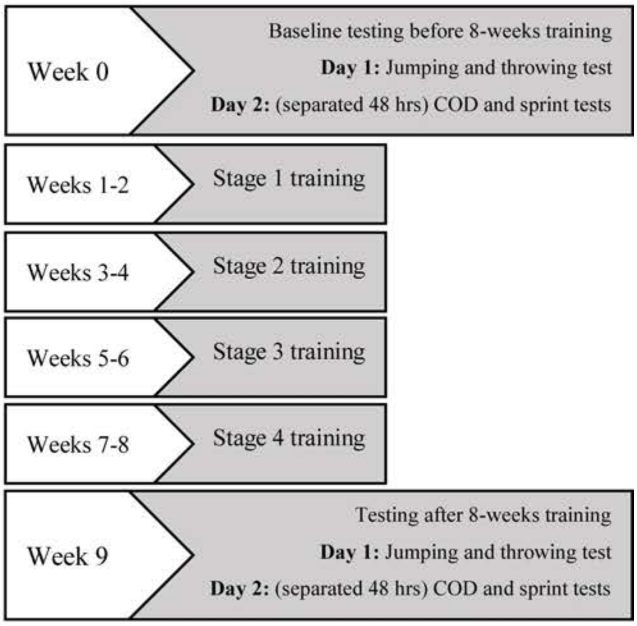

Figure 1. Testing timeline; COD: change of direction.

Figure 2. Cable resistance training (A) and iso-inertial training (B).

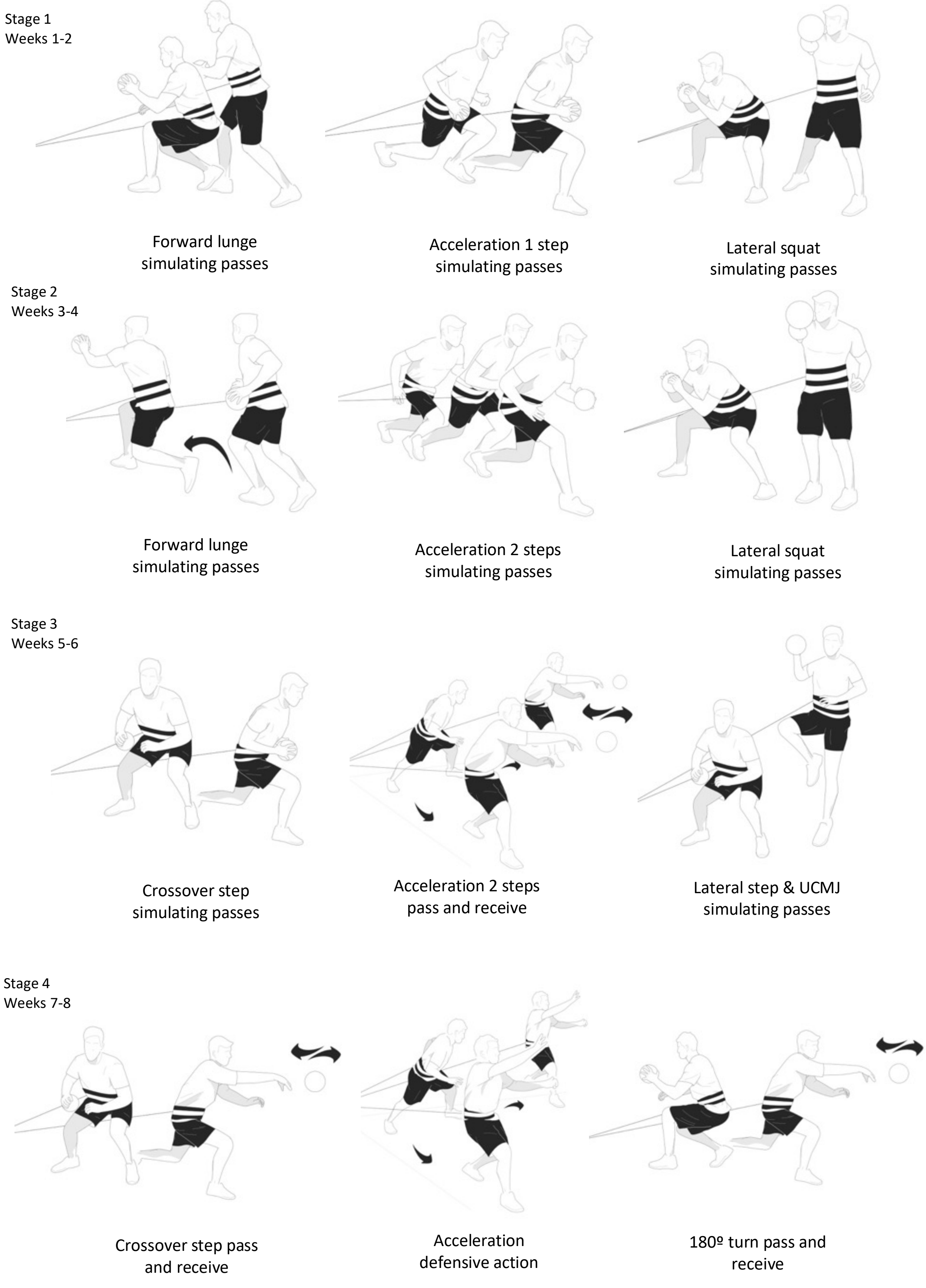

Figure 3. 8-weeks resistance training exercises and stimuli, following iso-inertial and cable resistance groups. UCMJ: unilateral countermovement jump

Discussion

DISCUSSION

A number of points of discussion can be drawn from the papers presented. Consequently, different topics considered as those that are most relevant to this research are discussed in this section, with the results obtained always analysed within the context of the most pertinent specialised literature.

INTER-LIMB ASYMMETRIES

Inter-limb asymmetries in chronological or maturational stage

As we were able to establish in our analysis, neuromuscular asymmetries can vary in magnitude depending on multiple factors. One of these can be the maturational stage of the athlete, which is why in Study 1, a comparison was made between the magnitudes of the asymmetries according to both the chronological age and the maturational stage of the subjects. This first study found that the largest asymmetry indexes in jumping actions were observed in the circa-PHV stage which. Likewise related to the jump, and in this case concurring with the results of our Study 1, Bishop et al. (70) record greater asymmetries in adolescence (U16) than in older age groups (U18 and U23) among young footballers. Another interesting aspect relating to the age and maturation stage of athletes was revealed in our Study 1 when the change of direction and balance actions were analysed. Greater asymmetries were recorded in pre-PHV (12 years old, according to chronological age). These results concur with Read et al. (149), who obtain greater asymmetry indexes in pre-PHV subjects in jump and balance values among young footballers, although their results were non-significant when the magnitude of the asymmetries were compared among the different stages.

Figure 11. Change of direction ability assessment.

Example of different changes of direction in a COD180º test (Study 1).

Based on our results in Study 1 and the various studies mentioned in the paragraph, it appears that there are fluctuations in magnitude and presentation of asymmetry across the different maturational stages, and mainly in pre-PHV and PHV, depending on the assessments analysed. This could be due to neuromuscular changes associated with growth (21,150,151). To this effect, to be able to observe the magnitudes of asymmetry in relation to different skills and sports and their effects on performance, Studies 2-5 are focused on the youth athlete populations who had already passed the PHV maturational stage, thus enabling the asymmetries to be compared without this factor influencing the results.

Inter-limb asymmetries in different skills

The existing literature has evolved in line with the functionality of the tests proposed to determine asymmetries between limbs. To this effect, the less functional tests have mainly progressed towards jump and change of direction assessments, such as were employed in the current thesis, with a view to achieving a greater correspondence to performance within the handball and tennis population examined. The two sports have in common the variability of the situations that can arise during competition and the multidirectionality that typifies their actions (31,36). These sports are known to differ in aspects such as the nature of the space in which they take place (shared/not shared) and the number of rivals and teammates, factors that must be taken into account when analysing the results obtained.

Change of direction inter-limb asymmetries

The ability to change direction is the skill that can be considered as the most important one in terms of the needs of the sports that are dealt with in this doctoral thesis, whether the space of play is shared or not. Despite the importance of the COD action within these sports, the tests that are usually administered to assess this skill are not sensitive enough to detect asymmetries between limbs, illustrated by the low percentages obtained in the different studies included in this doctoral thesis: Study 1 (COD180: 2.09%), Study 2 (COD180: 2.6%), Study 3 (COD180: 1.83%), Study 4 (COD90: 3.39%; COD180: 2.12%). This trend of results has been observed in other sports such as basketball in COD180: 1.71% (74), team sports (soccer-rugby-cricket) in COD180: 3.8% (105) and in COD180: 2.74% and COD90:4.93% in the same team sports (99), netball in COD180: 2.3% (83) and football in COD180: 2.39% (67).

Despite the generally small magnitude recorded in inter-limb asymmetries in change of direction tests, it seems that those carried out with COD90 may reveal higher values in multidirectional sports. The results obtained in Study 4, carried out with handball players, coincide with the asymmetry values (-4.93%) found in other multidirectional sports (99).

Following the line of work of Nimphius et al. (152) and Dos'Santos et al. (83), the variable CODD was introduced in Study 4 with the aim of achieving greater sensitivity for the detection of in the change of direction asymmetries. To this effect, the asymmetry results for CODD in Study 4 were higher than those obtained for COD in the same analysis. More specifically, the magnitude of the asymmetry for CODD90 was 10.52%, while the same variable for COD90 was 3.39%, despite being smaller than those found by Dos'Santos et al. (83). Study 4 also observed that magnitude of CODD asymmetry was larger in CODD90 (10.52%) versus CODD180 (5.48%) in relation to the angle of the change of direction. This result is important given the large number of actions carried out at this angle in handball (a sport analysed in this study).

As mentioned previously, the CODD calculation can be understood as a variable that enables us to isolate 'the moments of the change of direction'. Subsequently study this skill in greater detail to see whether problems in this action really do exist, or whether the results obtained are influenced to some degree by the sprint immediately before and after the actual COD. The characteristics of this phase of the change of direction have been addressed in different chapters of this doctoral thesis, with special attention paid to balance, trunk stabilisation, and eccentric muscular action at the moment of deceleration as important aspects of neuromuscular control (25,37,40,41,114). The set of CODD values and the analysis of the factors that can influence the change of direction can provide information (i.e. magnitude, direction of asymmetry, speed values) for designing training programmes related to neuromuscular control in this skill with the dual objective of improving performance and preventing injury.

Regarding the repeated COD test, the results demonstrated larger magnitude of asymmetry than those measured in a test of the same skill without the resistance-testing device. This result is perhaps to be expected given the longer duration of the test, which may therefore magnify any asymmetry which is present, these higher values. In Study 2, which was the first time this test was used to determine inter-limb asymmetries in these skills, the values obtained were 5.8%. These data would suggest that repeated COD test consistently reveals also larger magnitude of asymmetry in comparison to conventional COD tests in handball and tennis players.

Jumping inter-limb asymmetries

As explained in the introduction to this doctoral thesis, jump tests are the most used tests to determine inter-limb asymmetry due to their high reliability and sensibility (53,69). Among the different types of jumps that can be assessed, the vertical countermovement jump shows largest magnitude of asymmetry in female youth soccer players (69), and elite male youth soccer players (103). This finding coincides with all the studies included in this doctoral thesis, since the greatest asymmetries were always obtained in this test.

As shown in Figure 12, the vertical jump demonstrates the largest magnitude of asymmetry and with other types of jumps (with different force vector application) as when it is compared with other types of tests, and this result is constant across different sporting specialities (74,103). This can be understood if we start from the basis that the vertical jump test is the simplest (most elemental) coordinative action of all the tests compared in the asymmetries study, opposite to the lateral and horizontal force vectors in the unilateral jump and other types of actions like the COD and the sprint. This consideration, from which multiple discussions could be started, can be explained first by the clear involvement of the sural triceps (153,154). As one of the main muscles involved in this action, its fibres – anatomically speaking – have a longitudinal orientation in the direction the vertical jump is executed (154). This coordinative simplicity is further supported by this jump test being carried out on a single, spatial plane. All these factors make the execution of the jump less subject to the involvement of other muscles, as happens in the action of the lateral and horizontal tests (forwards). The change of direction action, on the other hand, is the most complex from a coordinative point of view, since it combines the three planes in the same action. To this effect, the new method for detecting inter-limb asymmetries with iso-inertial resistance becomes even more important, because apart from combining the three planes of movement there is also greater involvement of the neuromuscular system due to the increased requirements of the eccentric overload in the different phases of the change of direction.

The characteristics of play in both handball and tennis mean that the jumps are executed with a preferred leg, which is normally the opposite one to the limb that is throwing or hitting. This can lead to greater inter-limb asymmetries due to the same limb repeatedly carrying out the same action (68). However, the directionality of the change of direction actions is subject to how the game develops, which hypothetically, means it is less likely for a clear direction of COD dominance to be established.

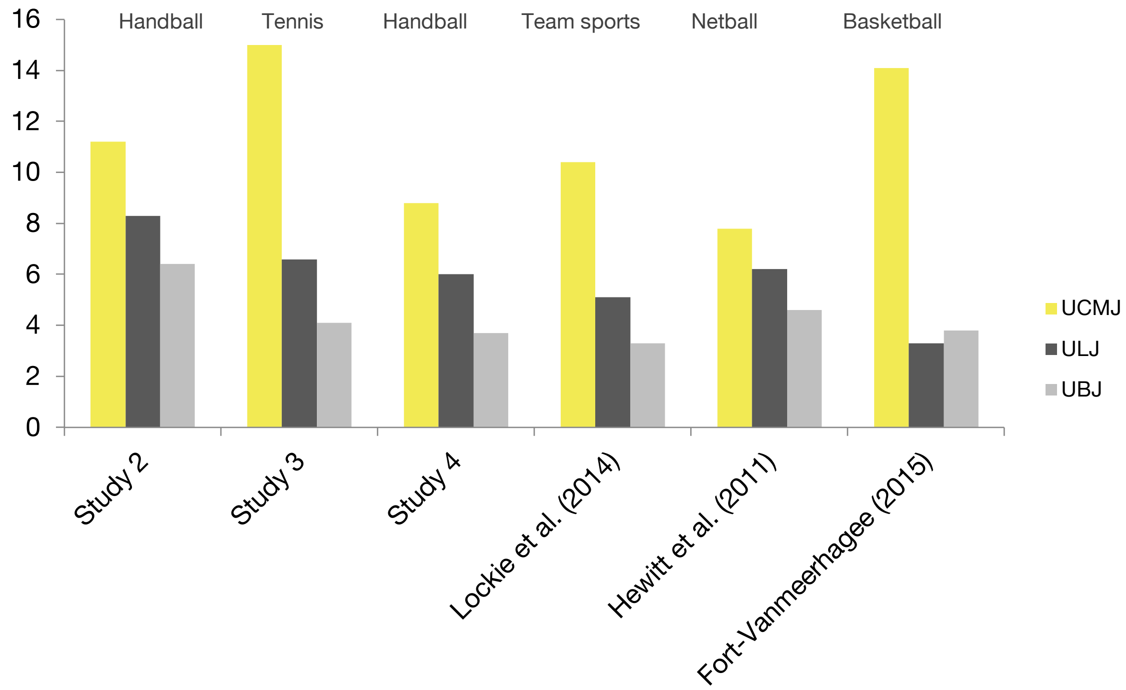

Figure 12. Jumping inter-limb asymmetries in different sports
Figure representing the inter-limb asymmetries found in different jump tests in multidirectional sports.
UCMJ: unilateral countermovement jump; ULJ: Unilateral lateral jump; UBJ: unilateral broad jump.

Figure 12 shows different magnitude of inter-limb asymmetry in each type of jump test, depending on the sport. This brief comparison shows the differences between and fluctuations in magnitudes between the two sports featured in Studies 2, 3 and 4, and among other specialised sports in which teams share a space. This set of results demonstrate the need to individualise tests depending on the sport to obtain valid, useful data that is relevant to each specific situation.

The iso-inertial device: new method to detect inter-limb asymmetries in motor-skills

In the analysis previously made of the literature related to iso-inertial devices, we reported how these can accentuate the eccentric phase (131) of tasks and elicit positive adaptations in the performance of a stretch-shortening cycle (131,132). Studies 3 and 4 were carried out with the aim of using the advantages of this system to study and detect asymmetries. A new method to detect inter-limb asymmetries in change of direction actions with eccentric overload was established in these studies, which enabled this action to be isolated (isolating in the COD action in a different way to the CODD) and a performance within a task bearing greater correspondence to a specific sport action to be obtained. This approximation of the sport itself is circumscribed by the kinematics of the action and the existing dynamic demand, produced because the resistance of the device can simulate the effort required of a prior sprint (concentric phase) and the consequent need to decelerate (eccentric phase).

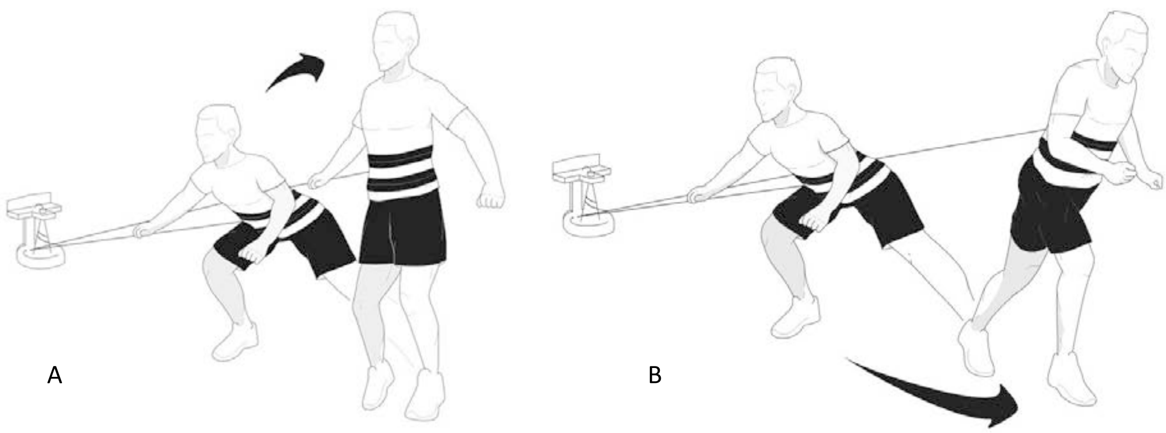

Figure 13. Testing conducted on the iso-inertial device in Studies 3-4.
A: lateral shuffle step (LSS), start and brake phase; B: Crossover step (CRO), start and brake with the right leg phase.

Figure 13 shows the crossover step and the shuffle lateral step analysed in Studies 3, moves that are considered to represent an approximation of the change of direction actions typical of the sports focused on in the main thread of this doctoral thesis (Study 3: tennis; Study 4: handball).

Considerably larger magnitudes are recorded in Studies 1 and 4 than in the COD180 test (Study 3 and 4) and the COD90 test (Study 4), and also in comparison to other authors' findings in a different COD test (-2.81%) (83). Furthermore, the iso-inertial methodology enables us to allows the eccentric and concentric components to differenciate, as can also be seen in Figure 14.

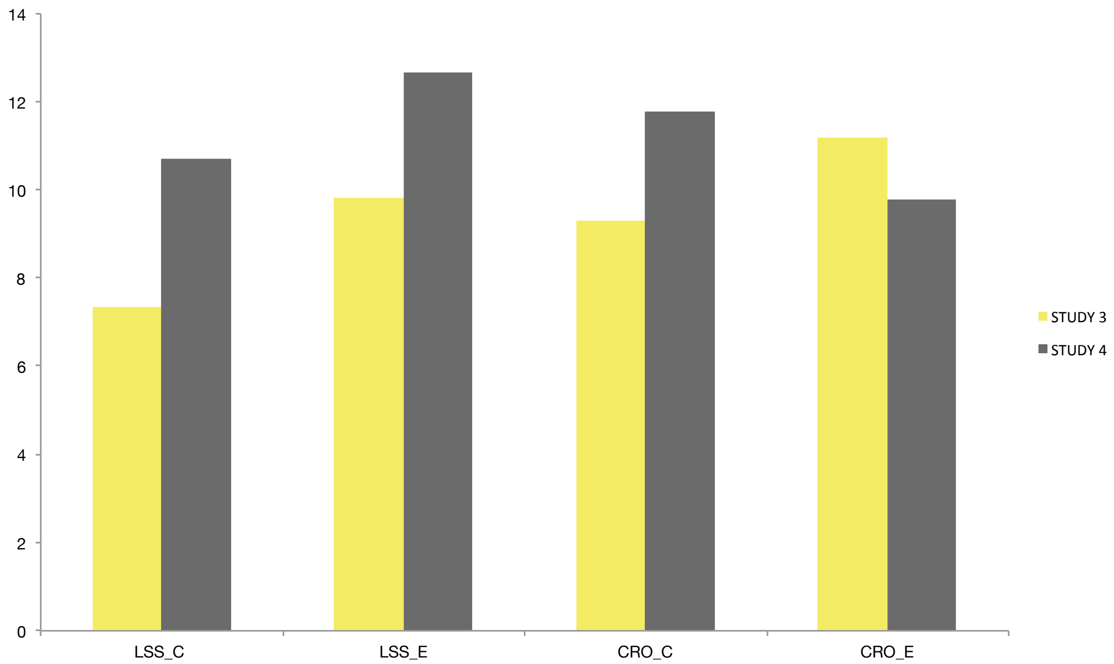

Figure 14. Change of direction inter-limb asymmetries in different multidirectional sports.
Figure showing the inter-limb asymmetries in change of direction actions using an iso-inertial device in two multidirectional sports. Study 3: tennis; Study 4: Handball LSS: lateral shuffle step; CRO: crossover step; C: Concentric; E: Eccentric.

This is the first time this methodology has been used to detect inter-limb asymmetries, enabling us to examine a task designed to isolate the COD action and to analyse the existing imbalances in the concentric and eccentric phases of the tasks assessed. Regarding the two sports studied in this doctoral thesis, we observed that larger inter-limb asymmetries are obtained in handball for all the variables analysed, with values that oscillate between 11.8% and 12.7% in the concentric and eccentric actions of the LSS and the concentric action of the CRO.

These larger magnitudes of asymmetry associated with COD tests with iso-inertial resistance means that this assessment may be more sensitive in regard to the detection of asymmetries in comparison to the other assessments utilized within this thesis. It is also important to highlight the importance of this type of assessment with iso-inertial resistance, due not only to its coordinative complexity – compared with other assessments to detect inter-limb asymmetries – but also to its greater functionality.

Figure 15. Inter-limb asymmetry assessment with iso-inertial device.
Example of testing conducted on the iso-inertial device in studies 3-4. A: Crossover step (CRO), brake phase with the right leg, acquiring the variables of concentric and eccentric power in the different phases of the change of direction.

These results lead us to consider it important to include this assessment with iso-inertial resistance (figure 15) in the battery of tests that can be applied to multidirectional sports, and to be able to construct neuromuscular profiles depending on muscular actions (concentric and eccentric), specific actions, type of COD (effect of angle, crossover and shuffle lateral) and the characteristics of the sport (movement profile).

Inter-limb asymmetry direction

The directionality of asymmetries was also mentioned in the introduction to this doctoral thesis. Bishop et al. (103) recently focused on this aspect in different jump assessments, showing the individual profile of the directionality of asymmetries in young footballers, and highlighting their variability. The direction of the asymmetries was addressed at an individual level in Studies 2, 3, and 4, also with the aim of investigating specific objective 1. Although this aspect was not one of our main concerns, in Figure 16 we show the percentage agreement of the preferred leg among the different skills assessed in each of the different cross-sectional studies carried out (studies 1-4).

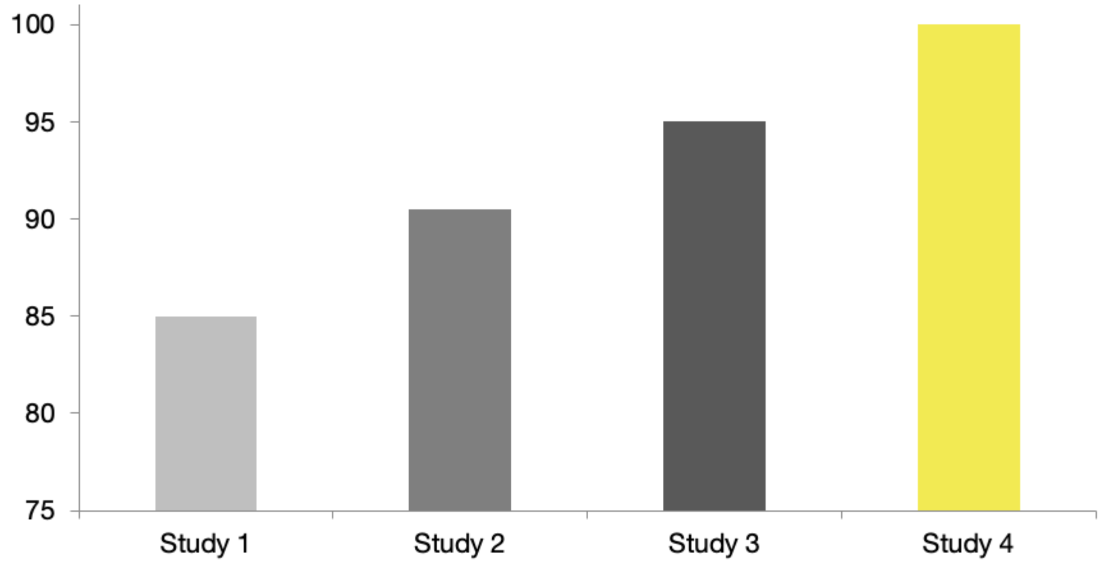

Figure 16. Percentage of preferred leg (i.e. left-right) non-coincidence in different studies
This figure shows the relation (in percentages) of the preferred leg non-coincidence for all the tests of each of the cross-sectional studies of this doctoral thesis. This analysis clearly demonstrated the low coincidence of the preferred leg depending on the tests carried out in the sports analysed in this doctoral thesis (tennis and handball).

The inter-limb asymmetries direction, however, was only published in Studies 2 and 4. The preferred leg non-coincidence (in relation to the directionality of the inter-limb asymmetries) for the set of tests in each study can be seen to be very high, meaning that a high individual variability for the dominant leg was identified depending on the skill being assessed. These values show that determining the dominant leg depends on the type of performance test employed and the specific variable/s considered.

The directionality of the asymmetries was shown in Study 4 with similar tests (i.e. jumping, COD tests) grouped together, as shown in Figure 17. The percentage of agreement (right-left) in relation to the different sports in question can be seen, even though these skills have been grouped without considering possible differentiating elements such as the jumping force vectors applications and the CODS angles.

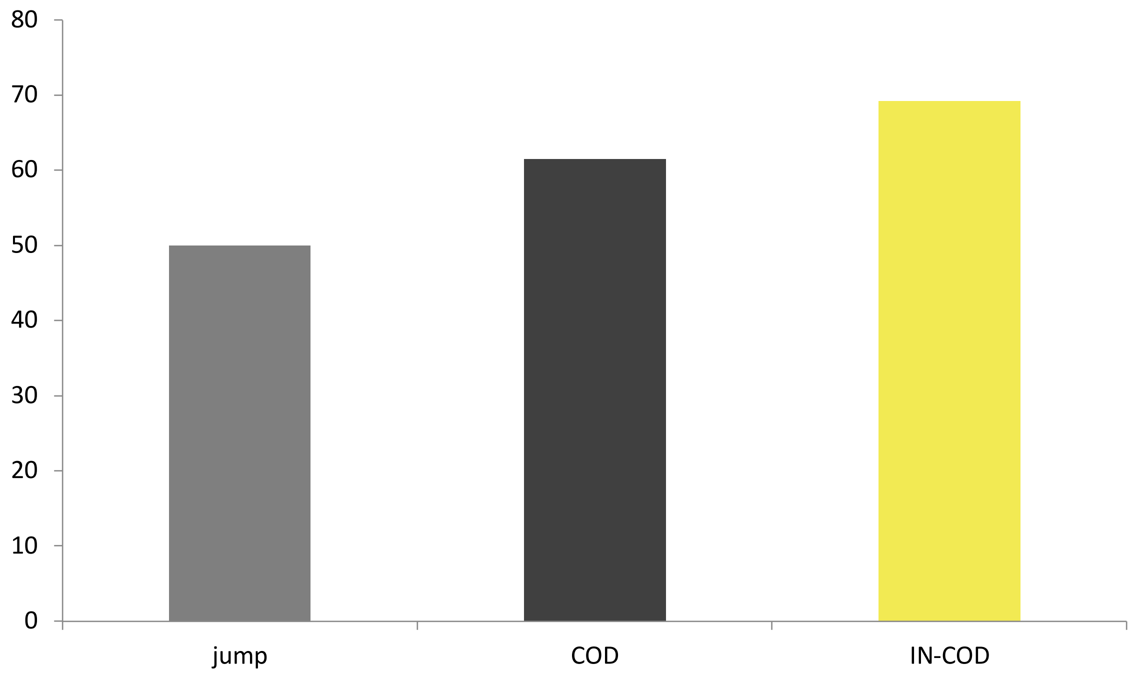

Figure 17. Percentage of preferred leg (i.e. left-right) non-coincidence in different abilities (Study 4)

This figure, complied from the values obtained in Study 4, shows the relation (in percentages) of the preferred leg non-coincidence, analyzing the different tests for each skill: jump (UCMJ, ULLJ, UBJ); COD (COD90, COD180) and IN-COD (LSS_C, LSS_E, CRO_C, CRO_E,). This analysis clearly shows the low coincidence of the dominant leg in the different tests of each skill.

UCMJ: unilateral countermovement jump; ULJ: Unilateral lateral jump; UBJ: unilateral broad jump; LSS: lateral shuffle step; CRO: crossover step; C: Concentric; E: Eccentric.

These data highlight the importance of taking the individual profiles of inter-limb asymmetries into account, considering the skill, force vectors, change of direction angles, the analysis of concentric and eccentric muscle power, and the complexity of the actions. The type of test selected, the degree of correspondence (57), the role of the athlete in the field (related to their personal skills) (108,109), and the status of the subject (healthy, or with an acute or chronic injury) should also be considered.

Inter-limb asymmetries: effects on performance

One of the main focuses of attention of this doctoral thesis, which is related to specific objective 3, is the effect of inter-limb asymmetries on the performance of the different skills assessed (jump, change of direction, and sprint). Bishop et al. (69) recently highlighted how high magnitudes of inter-limb asymmetry in the vertical jump are associated with lower performance levels in that jump and slower times in the 5, 10, and 20m sprint in youth female soccer players. The same authors (67) also reported how asymmetries in the drop jump are associated with lower performance levels in the 30m sprint (higher times) and the COD 505 test in adult female soccer players. In Studies 2 and 4 of this doctoral thesis, conducted with young handball players, and in Study 3, which focused on tennis, the moderate effect of inter-limb asymmetry magnitudes on the performance of different sport skills was also identified.

One of the limitations of these results is that we did not assess performance in exactly the same way in the different studies, making it difficult to reliably map the effect of inter-limb asymmetries on the performance of different skills. Consequently, a summary of the findings of Studies 2, 3 and 4 related to this point is given in Table 3.

Table 3. Relations between inter-limb asymmetries and performance

IA	Performance							
	UCMJ	ULJ	UBJ	COD900	COD180	V-CUT	8X10	20M
UCMJ	*2* (r=-0.47)						2 (r=0.40)	
ULJ		*2* (r=-0.52)	*2* (r=-0.32)		2 (r=0.31 4 (r=0.39)	2 (r=0.32)		
COD180	*3* (r=-0.53)				3 (r=0.50-0.63) 4 (r=0.42-0.46)			
CRO_C				4 (r=0.51)	4 (r=0.51-0.41)			4 (r=0.46)
LSS_C				4 (r=0.44)				

N**ote*:** Table summarising the findings of the different studies in relation to the effects of inter-limb asymmetries on the performance of different skills. The numbers correspond to the different studies of this doctoral thesis in which these results were demonstrated and correlations.
IA: Inter-limb asymmetries; UCMJ: unilateral countermovement jump; ULJ: Unilateral lateral jump; UBJ: unilateral broad jump; CRO: crossover step; LSS: lateral shuffle step; C: Concentric.

Change of direction inter-limb asymmetries: effects on performance

The two sports analysed in this thesis show how a high magnitudes of inter-limb asymmetry in COD180 moderates relations with lower performance in this test, and literature aims to expect that higher asymmetry in a test can translate to lower performance in that test. However, as we have already mentioned, this type of test cannot isolate the true action being assessed and as such is a limitation in terms of the test's ability to specifically assess the change of direction. It is, nonetheless, a hugely functional test which is important to administer when assessing an athlete's skills. This test combined with the change of direction with iso-inertial resistance test using the methodology presented in Studies 3 and 4 of this doctoral thesis is an interesting possibility. This methodology enables the action of the change of direction to be isolated for independent analysis– as we have mentioned in previous sections- and power variables in the concentric and eccentric phases of the action to be obtained. Using this method, we were able to establish a relationship between high magnitudes of asymmetry in the concentric phase of the crossover test and lower performance in the COD90, COD180, and linear 20m sprint tests. The relationship with this decrease in performance can be explained by the difficulty to accelerate, although we do not know the nature of this happening, and a possible reason focused on the difficulty for some athletes when breaking and looking for stabilization before changing the direction of movement remains unclear. In the same line, we can also consider the linear sprint as a high complexity action, primarily due to the continuous neuromuscular readjustments required in each stride where maximum velocity must be maintained. This finding only applies to the study focused on handball, not on the study with tennis players.

Given that both our results and the relevant literature reviewed demonstrate the negative association that high inter-limb asymmetries magnitudes haves on the different performance tests, it is important to continue investigating in this line to be able to detect which magnitudes of asymmetry can lead to reduced performance in different skills. Especially relevant, and concurring with Maloney (68), how these inter-limb asymmetries can affect performance within the sports context must be established - a huge challenge given the difficulty in identifying the variables of study and their reproducibility.

Jumping inter-limb asymmetries: effects on performance

The negative effect that high magnitudes of asymmetries in the unilateral vertical jump have on performing this type of jump has already been mentioned. Larger asymmetries in the lateral unilateral jump are also negatively associated in performance in both the lateral jump and the horizontal jump, while the magnitudes of asymmetry in the horizontal jump demonstrate no relationships on performance of the different types of jump. These data show that there is a relationship we can consider as expected between greater asymmetry in a test and a reduction in performance in it.

If we focus on inter-limb asymmetries in jump tests and the associations they may demonstrate with performance of the most complex skills, we cannot establish a direct relationship that is dependent neither on the main axis upon which the action is developed nor on the level of coordinative complexity. This is true for both the tests presented in the different studies of this doctoral thesis (change of direction, capacity to repeat changes of direction, and multidirectional change of direction tests) and in the sprint actions. Although it has been observed that higher magnitudes of inter-limb asymmetries in the lateral jump are most strongly associated with negative performance outcome in the change of direction, these findings could only be found in handball, and not in tennis. This is difficult to explain, but it may be that the highest asymmetry magnitudes in the lateral jump are because there is clearly a dominant leg in handball jumping actions. What is more, in handball these actions consistently occur in the presence of external perturbation (i.e. opponent's challenge), when there is direct opposition from one or more opponents, adding to the neuromuscular complexity of the action that is usually jump with one leg (dominant leg in the jump). On the other hand, tennis players do not usually jump, and it may be rationalised that their displacement needs are generally less varied in relation to the direction of execution than handball players, that means tennis players' movements are more consistent in performing near COD 180° when playing. This could produce a greater balance between the lateral displacements on either side, thus diminishing the possible effect that the asymmetry of the lateral jump could have on performance in a change of direction test. Based on the results of the different studies, it is important to point out that due to the nature and fluctuations of the magnitude of the asymmetries recorded in the different tests, the effects on performance must be related depending on the test assessed, as suggested by Bishop et al. (55,103)

COORDINATIVE STRENGTH PROGRAMME

Study 5 was based on the hypotheses and objectives of this doctoral thesis, and on the different cross-disciplinary studies carried out (1, 2, 3 and 4). It was a longitudinal study (randomized parallel group design) that examined the effectiveness of an iso-inertial intervention on the reduction of asymmetries and improvement of performance. For these reasons, and given the diversity of motor actions and the important role played by perceptive and cognitive aspects, the fifth study of this thesis was based on a sample group of young handball players. Regarding the different strength methods, traditional resistance training is the most well-known and used of the strength training programmes in all its variables (Kettelbell, seated machine, free weight, cable resistance), and has been identified by its positive effects on sport performance

(112–114). For its part, iso-inertial training has been proposed as a useful tool in strength work among athletes (127,128,130,135), an important feature of which is that an eccentric overload can be caused (131), which is a positive aspect, especially in terms of the work involved in the braking actions in different skills. Furthermore, eccentric actions create enormous tension in the passive tissue, inducing physiological stimuli that may be anticipate to facilitate the hypertrophy processes (155). To this effect, it is important to consider the fact that positive adaptations take place in the tendinous structure, which is fundamental in explosive actions, where there is a balance between synthesis and the breakdown of proteins (156). The training load in Study 5 was decided with this consideration in mind, introducing the required recovery time between sessions and causing an eccentric work that was intense enough to be able to increase elastic properties such as stiffness, while hardly increasing the transverse section of the muscle and facilitating, according to the literature, an increase in collagen density (157). These physiological considerations, together with the functionality to be able to design actions that approximate sports skills, are what prompted the use of the iso-inertial methodology in the fifth study of this thesis.

In light of the above, and after analysing the different possible methodologies for strength work, we focused on comparing two methods that enable an similar functional programme to be developed, with the aim of making any possible existing differences between the two the type of resistance modality employed, and not due to any potential differences between the programmes designed. Apart from this initial premise, another defining characteristic of the programme was that it showed the functional tasks, with actions that represent the work of different motor skills (especially the change of direction). Given these needs, a conical pulley was chosen for the iso-inertial work and the gravitational force was developed by means of a cable (cable resistance training). One of the novelties of this training programme is how the loads applied in the different groups were managed using the rate of perceived exertion, which has been applied in different traditional resistance training works (158), but has never before been applied in iso-inertial or COD training programmes.

Exercise creativity

Despite it not being a point of discussion in Study 5, the importance of the type of task carried out in the intervention in this study should be mentioned. This 8-week training programme (preceded by a week of familiarisation) was based on change of direction tasks with a high coordinative demand and, as already explained, exactly the same movement patterns was carried out with the two groups (cable resistance and iso-inertial). The tasks in this programme were of increasing complexity, starting from an initial phase of technical learning and ending with a high level of difficulty in both coordinative and perceptive aspects (Figure 18). This complexity was interpreted from a holistic perspective, with the aim of approximating ecological construct (159). Different studies and theories defend this type of work (144,146) although, as far as we know, no existing studies have introduced the perceptive elements mentioned in a coordinative programme against resistance and comparing gravitational and iso-inertial methodologies.

The aim of this type of intervention was to impact on strength work that approaches sport specificity. This closer approximation of the coordinative demands of the sport is designed to cause adaptations in performance resulting from strength, coordination, muscular control, and motor skills work (change of direction, turns, accelerations, and jumps). Furthermore, based on the development of these four elements, the aim was to progress towards working on sport specific skills under an added resistance. Another aim was to accentuate the perceptive abilities of the players following strategies proposed by Vickers (32) introducing passing and receiving actions into the resistance work. The incorporation of the ball in passing practices, and the introduction of limited opposition – defenders with a handicap – enabled us to vary the athletes' focus of attention doing the resistance work. This type of stimulus is introduced to accentuate the fluctuations caused by introducing different attentional focuses, forcing more varied neuromuscular adjustments and time organisation.

Figure 18. Progression of the tasks carried out in Study 5.
This is a visual representation of the tasks carried out in Study 5 in which cable-resistance training and iso-inertial training were compared. A video representation of the tasks carried out in the iso-resistance training can be seen in the QR codes.

Effects of resistance training on performance and inter-limb asymmetries

One of the objectives of this thesis was to determine the effects of an iso-inertial training versus cable-resistance training. With this intention was designed and executed the study 5. Both resistance training programs showed improvements in the motor skill variables. When comparing groups, greater performance effects were found in favor of the iso-inertial training in change of direction (COD180, V-Cut test and repeated COD), jumping tests (UCMJ, ULJ and UBJ) and handball throwing test. Moreover, greater inter-limb asymmetry reductions in UCMJ were shown in the iso-inertial group, in comparison to the cable-resistance training group.

To understand why significant results were only found when working with iso-inertial devices (inter-group comparison), we must turn to the studies mentioned previously that explain the larger eccentric overload that can be achieved and the greater need for stabilisation at the end of the eccentric phase (131) and in the transition between deceleration and acceleration in the different tasks that make up the training programme. These requirements are greater in the iso-inertial training than in the cable-resistance training because during the braking phase resistance tends to increase, and is at its maximum in the eccentric – concentric transition. All this helps us to explain why the unilateral work in multiple and specific change of direction actions with iso-inertial resistance is effective in improving performance. Moreover, beyond the kind of strength training methodology, the introduction of sport specific stimulus when performing the different tasks of the training program may mean a more real adaptation to sport situations. This is an important reason to continue the research of greater specificity of the setting and stimulus presented when designing strength tasks.

In jumping tests, greater effects were found in UCMJ, ULJ_{ND} and UBJ for the iso-inertial group, while only UBJ showed improvements in the cable-resistance group. Recently, Gonzalo-Skok et al. (128), comparing a bilateral squat action to a program consisting on six coordinative exercises with iso-inertial resistance, found better improvement in the axial axis in the squat group, while the most varied exercising group found better results in lateral and broad jumps. The results of this study support the value of the specificity of training, although our work, according to our results, emphasize also the iso-inertial training as the methodology to improve in all tests performed. This finding is so clear when analysing the positive effects on jumping performance after our intervention, considering that the design of this program was non-focused on this motor skill. It could be possible, according to the work of Gonzalo-Skok et al. (128), that the great variability of the designed program (tasks and stimulus presented), performed in a great number of force vectors, could improve adaptations to all the motor skills tested.

Related to jumping asymmetries, differences on favor of iso-inertial group were found in UCMJ, but not in ULJ and UBJ. These results are in contrast to Gonzalo-Skok et al. (104), who showed a reduction in inter-limb asymmetries in the triple-hop jump test after a 10-week iso-inertial resistance training programme. This intervention consisted of a lateral lunge task in which different workloads were applied to the dominant and non-dominant legs. These findings aims to continue the investigation focused on training programs to reduce inter-limb asymmetries.

Last, the response of the horizonal jump (broad jump) skill to the training programme carried out in Study 5 should be discussed in this section. The test produced a change in the dominant limb in 23% of cases (Figure 19). In other words, this percentage of subjects recorded higher post-intervention values in the contralateral leg than was recorded in the leg with the highest value in the pre-test. From the point of view of the training effect, it is interesting to appreciate how this test can not only reduce asymmetries but can also change the direction of dominance. There are no data in the existing literature to compare these results after a post iso-inertial resistance intervention, but they may be explained if we consider that the horizontal jump is the type of jump with the least transference in handball. We cannot say that this jump is inexistent in this sport, but the vertical and lateral force vectors certainly predominate over the horizontal ones. Taking this into account, we can understand that subjects' results can vary in this test.

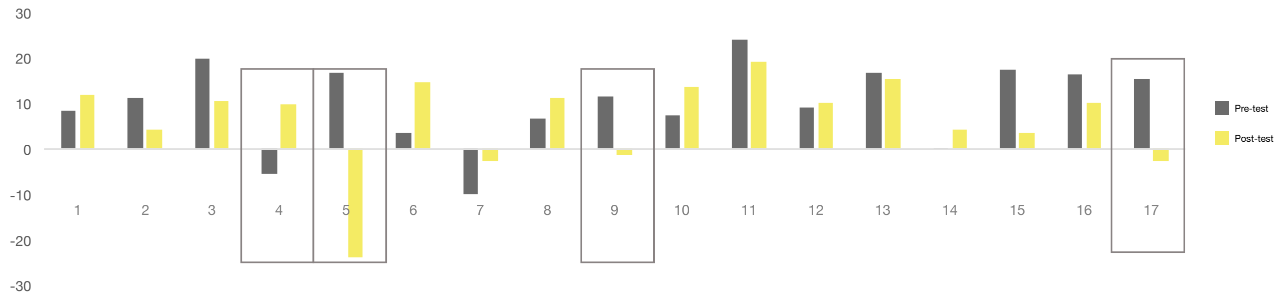

Figure 19. Inter-limb asymmetries direction
This diagram shows the changes found after an 8-week intervention of COD training with inertial resistance. The example used is the unilateral broad jump test (UBJ), and out of a sample of 17 subjects a change of preference as to the dominant leg was observed in subjects 4-5-9-17.

Conclusions

This doctoral thesis was based on five studies, which together comprise its main body. The following conclusions, ordered chronologically and not by order of importance, are drawn from these papers and their interconnections:

- The inter-limb asymmetries detected in multidirectional sports like handball and tennis (conditions of shared and non-shared spaces) vary in magnitude depending on the test administered. Hence, it is recommended that tests are selected depending on their specificity in relation to the sport speciality of the athletes.

- The limb exhibiting greater performance within a given tasks was highly variable, thus de direction of asymmetry is highly task specific.

- Larger asymmetries in the jump are found in the PHV phase, corresponding to the period of puberty. These findings are interesting to bear in mind when analysing motor skills to be able to relate the results with athletes' maturational stages.

- The change of direction with iso-inertial resistance, the value of the CODD variable and the repeated COD, demonstrate larger magnitudes of asymmetry in comparison to the other COD tasks (COD90, COD180) evaluated in both handball and tennis players.

- The vertical jump shows larger magnitudes of asymmetry in comparison to the other jump tasks (ULJ, UBJ) evaluated in both handball and tennis players.

- The change of direction with iso-inertial resistance tests could be of interest to isolated the study of this skill, in order to differentiate the analysis of the strength applied in the eccentric (breaking phase) and concentric (acceleration phase) actions.

- Moderate asymmetries were negatively associated with to performance in COD, linear sprint and jumping.

- Iso-inertial training leads to larger performance improvements in comparison with traditional cable-resistance training in performance tasks (multidirectional COD, capacity to repeat COD actions, jumping and handball throwing actions).

- Iso-inertial training leads to larger reductions in jump asymmetries in comparison with cable-resistance training.

Limitations and future lines of research

This doctoral thesis has several limitations, which are also mentioned in the various papers published, and must be considered when analysing and discussing the results. At the same time, they are potential starting points for future research.

In Study 1, the small number of subjects in the pre-PHV (n=8) and the U12 (n=6) sample groups could limit the potential of the results obtained when the different age groups are compared. Considering the importance of detailing the profile of asymmetries and performance in relation to both the different motor skills and maturational stages, the sample group in this type of analysis should be larger.

More knowledge about the iso-inertial load required in change of direction tasks is needed. We understand that the load that best represents the sport specific skill must be known, and this can be achieved by means of studying different force platforms and iso-inertial loads.

The results obtained in Study 5 show an interesting possibility for reducing asymmetries by means of strength work with iso-inertial resistance. More studies in this direction are needed since it appears that iso-inertial training not only has a greater effect than cable-resistance training, but it can also lead to better performance in some motor skills. The most important area of research that could emerge from this doctoral thesis is the design of strength work with iso-inertial resistance. The proposal developed in Study 5 combines strength work with motor skills, introducing perceptive stimuli that made the coordinated action involved more difficult. This methodology led to increased performance in some skills that are determinant in the sport, and a reduction in asymmetries in some of the tests. The aim when designing the programme was to make the strength work as close an approximation as possible of the specific requirements of the action within the sport, although we understand that this line of research can be pursued through either increasing and varying other perceptive elements, or by introducing decision-making elements.

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DOCTORAL THESIS

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