Tesis Doctoral

CHANGES IN SWING HIGH BAR PERFORMANCE AND COORDINATION: SKILL ACQUISITION AND FINE TUNING SKILL

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Chapter 1. Introduction

Introduction

Movement is the way in which an individual acts upon and interacts with the environment. Across the lifespan new movements are learned, they evolve, and on occasion, get dissolved in relationship with the individual aims and motivations. For example, around the first year of life infants finally take their first independent walking steps, and soon crawling will be replaced by walking as the main form of locomotion. During the next year infants will improve their independent bipedal locomotion, enough so that they are able to achieve the required momentary flight phase of the run (Clark & Phillips, 1993). Many studies have been conducted over the last century to understand how humans learn to control and coordinate their movements (Grillner, 1975; Kelso & Clark, 1982; Skinner, 1938; McGraw, 1945; Thelen & Ulrich, 1991; Woollacott & Shumway-Cook, 1989). Learning a new movement allows subject to resolve a motor problem, and therefore achieve the aim of a new task. However, this process of learning can typically continue until the individual performs the skill with maximal efficacy (better expectations in their results) and efficiency (minimal expense of energy and time) (Riera, 2005). It is widely accepted in the scientist literature to divide the human movement learning process into two periods: (1) skill acquisition, when the person is faced with a novel task, the subject has to elaborate a new movement to achieve this task goal; and (2) fine tuning period, when the goal of the individual is to adjust the parameters of a previously learned task to become more efficacy and efficiency (Clark, 1995; Delignieres, Nourrit, Sioud, Leroyer, Zattara, & Micaleff, 1998; Newell, 1991; Temprado, Della-Grasta, Farrell, & Laurent, 1997).

Considering the period of fine tuning skill, the specifics characteristics of the learned skill could be impacted by two other processes. First, the individual level of development as a biological maturation and second the accumulation of expertise capabilities (Fig. 1). As these processes advance with age, the individual capabilities will also change. For example, motor expertise's level could impact movement execution given that the accumulation of particular motor skills' practice during years could change physical, perceptual, and psychological attributes from what they were before practice (Gautier, Marin, Leroy, & Thouvarecq, 2009; Marin, Bardy, & Bootsma, 1999). In order to consider both processes, biological development and expertise, traditionally studies have examined the learning processes in relation to age (Fleisig, Barrentine, Zheng, Escamilla, & Andrews, 1999; Forssberg & Nashner, 1982; King, Kagerer, Contreras-Vidal, & Clark, 2008; Streepey & Angulo-Kinzler, 2002).

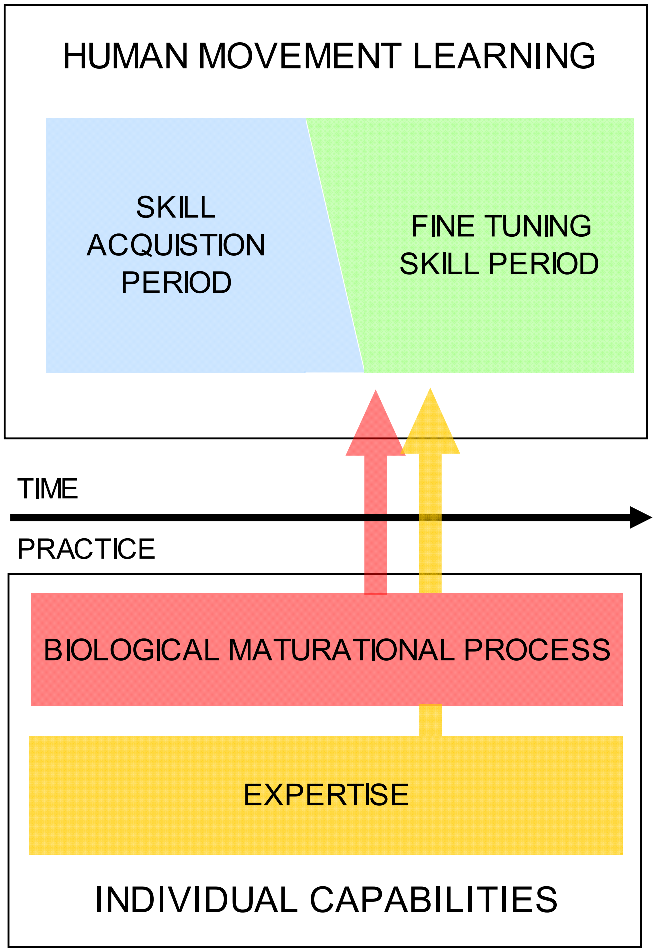

Fig1. Human movement learning schema with periods (skill acquisition and fine tuning skill) across time.

Human movement learning

A major concern of motor skill learning theorists is the underlying processes or mechanisms by which individuals refine their movements so that the goal of the activity is eventually achieved with a degree of precision and consistency (Sparrow & Irizarry-Lopez, 1987). It's important to note that moving in one's environment requires not only the coordination of appropriate muscle responses to a perturbation, but muscle responses that are coordinated continuously with ever-changing environmental and task demands (Whitall, Getchell, McMenamin, Horn, Wilms-Floet, & Clark, 2006). Moving adaptively in one's environment or learning motor skills are conceived as the search for the optimal solution in the motor-perceptual workspace (Fig. 2) (Nourrit, Deschamps, Lauriot, Caillou, & Delignieres, 2000; Walter, 1998; Whitall et al., 2006). Movement learning workspace can be defined as the interaction of action and perception where action includes performance and coordination and perception involves the integration of multisensory information and cognitive capabilities.

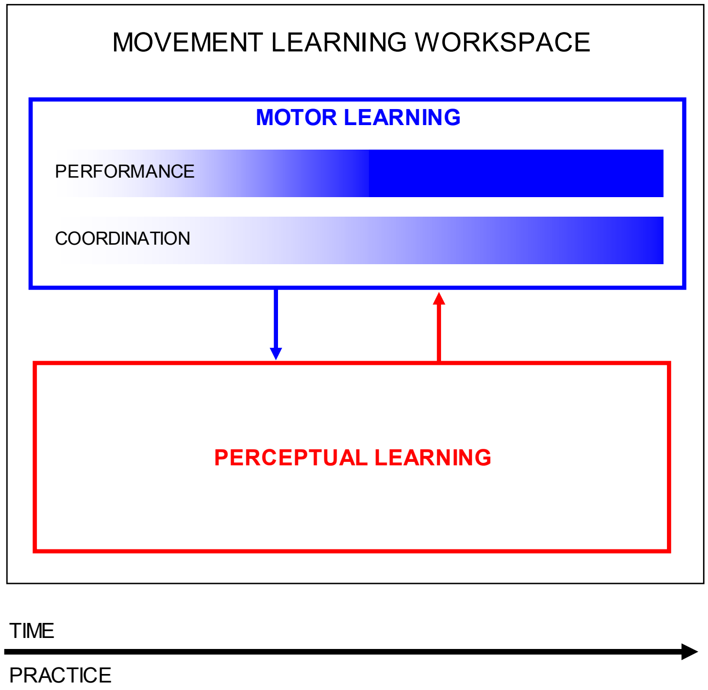

Fig. 2. Schema of the motor-perceptual learning workspace with interactions between motor and perceptual learning. In addition, it is also represented the time rate progress of the motor learning factors (performance and coordination) with darker shading as more advanced.

Motor Learning: performance and coordination

When the motor learning factors of the workspace are described, two approaches can be applied: (1) focusing in changes of the final results of the movements (performance) or (2) concentrating in the modifications of the spatio-temporal process to achieve movements (coordination) (Fig. 2) (Delignières, Teulier, & Nourrit, in press; Vereijken, van Emmerik, Bongaardt, Beek, & Newell, 1997). Changes in the measurable outcomes of the movements (i.e. performance) include variables as reaction time, amplitude of movement, or time placement of critical events. Focus only on the performance variables can mask how individuals change movements to achieve the goal task or adapt to new situations. Researchers in motor learning are also interested in the spatio-temporal relationships between segments (i.e. coordination) involved in the movements to achieve goal task (Angulo-Kinzler, 2001; Cheron, Bouillot, Dan, Bengoetxea, Draye, & Lacquaniti, 2001; Clark, Whitall, & Phillips, 1988; Vereijken, van Emmerik, Whiting, & Newell, 1992). Given that coordinative variables provide a conceptual link between the inside process and the outside performance (Bernstein, 1967), examining both types of variables (performance and coordination) can be the better way to understand the whole process of motor learning.

In fact, it has been proposed that performance and coordination progress in parallel but with different time rate during motor skill acquisition (Fig. 2) (Chow, Davids, Button, & Koh, 2007; Gentile, 1998; Hikosaka, Nakamura, Sakai, & Nakahara, 2002; Hung, Kaminski, Fineman, Monroe, & Gentile, 2008; Teulier, Nourrit, & Delignières, 2006). Considering this time rate difference, these authors suggested two stages in the process of learning a task. First, early learners attempt to establish appropriate performance as for example the appropriate placement of task events (spatial sequences of the movement). Second, the adoption of the dynamic control of the movement including the coordination mode is achieved later in skilled performance. This later stage allows better adaptation to the mechanical constraints of the task. Consequently, performers progress to produce movements that appear effortless and fluid (Chow et al., 2007). The early stage of learning is characterized by a relatively fast spatial sequence acquisition, while the dynamic control at the joint level improves parallel but at a slower rate. In fact, the early stage of learning involves starting with the skill acquisition period and working on achieving a minimal level of performance. As time evolves with more practice, the later stage of learning typically implies a fine tuning period where adequate level of coordination is acquired.

Perceptual Learning

Another important aspect of the workspace in movement learning is the perceptual component. Focusing on the perceptual factors, motor learning has been closely associated with the ability to correctly perceive the environment through peripheral sensory systems, as well as to centrally process and integrate visual, auditive, proprioceptive, and vestibular inputs (Hatzitaki, Zisi, Kollias, & Kioumourtzoglou, 2002). The coupling and integration of the multisensory information was demonstrated for example in the postural control (Jeka, Oie, & Kiemel, 2000; Perterka, 2002) and moving targets on a tablet (King et al., 2009). In fact, part of becoming skilled at a task involves learning to effectively use the sources of information available (Robertson & Elliott, 1996). At a behavioral level, perceptual learning reflects improvements in complex motor-perceptual-based skills as a result of training (Jackson & Farrow, 2005). It seems reasonable to suggest that perceptual capabilities and motor factors evolve and function together to support the acquisition and maintenance of motor skills.

The perceptual and motor learning relationship has been studied as a bidirectional process where there is transfer from perception to action as well as transfer from action to perception (Fig. 2). Perception to action transfer was examined applying observational learning such that the practitioner demonstrates the movement and the learner immediately imitates him. This type of transfer has been well studied (McCullagh, Weiss, & Ross, 1989; Vogt, 1996). In contrast, few studies have been conducted to analyze the contribution of the motor learning to perception, that is, changes in perception due to practicing a task (Hecht, Vogt, & Prinz, 2001). Hecht et al. (2001) demonstrated motor-perceptual effects producing timed sequences of sinosuidal arm movements using a mechanical lever, and visual task required judgments of time ratios of sinusoidal bar movements displayed on a monitor. Findings of these authors revealed positive transfer effect from perception to action as well as from action to perception.

Traditional Perspectives of motor learning

The question of how humans learn and refine their movements has received much attention, with scientists proposing many different theories. Although there is still considerable debate over which theory is most appropriate, the importance of developing a strong theoretical framework for studying skill acquisition and guiding practice remains. Two theoretical proposals around motor learning were developed during the last decades of the 20th century: neuromaturational perspective (Gesell, 1928; McGraw, 1945) and cognitive perspective (Keele, 1968; Schmidt, 1982). The neuromaturational perspective has been used primarily for skill acquisition in infants and young children, while the cognitive perspective has been preferred to interpret changes during adult motor skill acquisition.

According to the neuromaturational perspective *skill* is the result of the hierarchical structures of the central nervous system (CNS), and the formation of central pattern of generators that produce the sequence and timing of muscle activation (Grillner, 1975, 1981). This perspective sees the motor sequences learned by an individual as a direct result of the maturation of CNS. The stable progression through key motor milestones by an individual was viewed as evidence for the greater influence of evolution and genetics over environment or other changes occurring in the subject (anthropometrical dimensions, for example) (Davids, Button, & Bennett, 2008). With time, contradictions revealed in the motor milestone progression leaded several researches to focus more on the interactions between personal characteristics and the specific environmental context (Thelen & Smith, 1994). In fact, the relations between these critical factors to produce movement were not studied under the neuromaturational perspective.

The cognitive perspective understands learning as a product from previous internal representations of the movement and the formation of generalized motor programs available to the individual (Schmidt, 1982). This perspective postulated that motor-perceptual information can be represented within CNS in the form of abstract representations. With practice and experimentation in different situations such representations become motor programs or schemes. Following this perspective, a generalized motor program contains the general characteristics for a given class of movements such as walking, balancing, jumping, and bicycling. As experience is gained, the general motor programs can be adapted to the specifics of the task demands. This perspective assumed that movements arise from plans and instructions commanded by an executive. However, it does not explain neither who is this executive nor where the programs come from. In addition, the cognitive perspective works well to explain behavior at the performance level (end product variables such as reaction time) but it falls when trying to explain the emergence of a new task (for example onset of independent walking in toddlers) or the versatility of a skilled performer executing different tasks to accomplish the same task goal.

The principal weakness of the neuromaturational and cognitive perspectives is that they ignore the richness inherent in developing behaviors arising from many subsystems and processes (Thelen & Ulrich, 1991). Both approaches can be useful to understand motor learning when the task to be performed constitutes a variant of a previously learned task, but they are less easily applicable for the behavior of an individual facing a completely novel task (Delignieres et al., 1998). Techniques and tools to analyze motor learning were developed under the neuromaturational or cognitive point of view. However these tools were mainly used to describe behavior while elaboration, organization, and adaptation processes of the motor behavior were not explained. Therefore, both perspectives generally evaluated the effectiveness of the progress of learning with respect to performance, and ignored the coordination modes adopted by the individual to achieve this performance (Temprado et al., 1997).

Dynamical System Perspective

An alternative theoretical explanation that has been evolving during the lasts decades is the Dynamical Systems Theory (DST). DST emphasizes that an individual (the system) contains multiple inter-related open sub-systems, that is, sub-systems that interact among them and modify their behavior influenced by each other and/or the context. Movement is conceived as an emergent behavior that arises from the collective dynamic of all the contributing subsystems of the individual involved in the task performance. These may include neural status, biomechanical characteristics, experience, attentional level and visual precision (Kugler, Kelso, & Turvey, 1982; Thelen et al., 1991; Ulrich, Ulrich, & Collier, 1992).

Movement Coordination

In order to acquire a new movement, an individual must change the organization and control of a large number of variables from the different contributing sub-systems. Each variable that need to be controlled to develop a task represents one degree of freedom (DoF). Focusing on the motor aspects of the movement (performance and coordination), the DST approach considers that the individual (i.e. the system) is composed by interconnected pendular chains (i.e. limb segments). The DoF of the system are defined by the number and type of segments and axes that are involved in the movement (Meriam, 1966). The DST proposes that this relatively large number of DoF can be summarized on collective variables which capture the essence of the behavior. From this perspective, performance is typically defined and assessed by a global outcome of the system or by results in the critical events of the movement. On the other hand, coordination of the movement is defined as the stable spatial-temporal relationship among movement system components (i.e. limb segments and joints), to achieve the task's goal (Delignieres et al., *in press;* Irwin & Kerwin, 2007b). Furthermore, tools to assess coordination mode have been proposed under the DST approach (and later reviewed in this thesis). Coordination mode can be characterized as in-phase, anti-phase or out-of-phase. Limb segment and joint movements are in an in-phase coordination mode when they move in synchrony with a 0º phase lag between them. In contrast, the coordination is in an anti-phase mode when joints or segments move in opposite directions with a phase lag of 180º. However, multiple intermediate out-of-phase coordination modes exist between the in- and anti-phase coordinations.

One of the main concerns a novice individual must resolve when faced with a novel task is to discover an effective mode of coordination among the participating joints and limbs

(Bernstein, 1967; Hong & Newell, 2006; Stergiou, Jensen, Bates, Scholten, & Tzetzis., 2001; Temprado et al., 1997). Considering the body as a set of pendular systems, individuals in general show two ways to control the large number of DoF when faced with a novel task. One possibility is freezing some degrees of freedom by fixing and/or decreasing mobility of some joints. Another option is coupling joint actions decreasing temporarily the complexity of the limbs movements (Vereijken et al., 1992). However, when the motor skill improves these freezed or coupled DoF are released (freeing degrees of freedom) and incorporated in the control of the dynamic system.

Constraints

Motor learning in the DST approach is understood as a process that arises from the interaction of a system that is surrounded by constraints (Newell & Vaillancourt, 2001). These constraints have been categorized in organismic, task and environmental (Fig. 3) (Clark, 1995; Clark, 2002; Handford, Davids, Bennett, & Button, 1997; Holt, 2005; Kugler, Kelso, & Turvey, 1980; Marin et al., 1999; Newell, 1986; Nourrit et al., 2000; Thelen et al. 1994). The relative impact of these three categories of constraints on the movement varies according to the specific circumstances. The *organismic constraints* include such physical characteristics as weight, height, and body shape, together with psychological and emotional attributes which may deem an individual to be more or less talented a priory. The analysis of the initial state of the system (i.e. a-priory talent) constitutes a key point for understanding motor learning when an individual faces a novel task (Delignieres et al., 1998; Swinnen & Carson, 2002). Teulier and Delignières' study (2007) found that participants do not possess the same skill level at the beginning of practice and changes in their performance via further practice differed among them. These authors suggested that these differences could arise from individual-specific organismic constraints. That is, differences in the individual evolution of the behavior resulted from differences in the initial skill level of participants which, in turn, could be initially different due to differences in physique, psycho-emotional attributes and experience among participants.

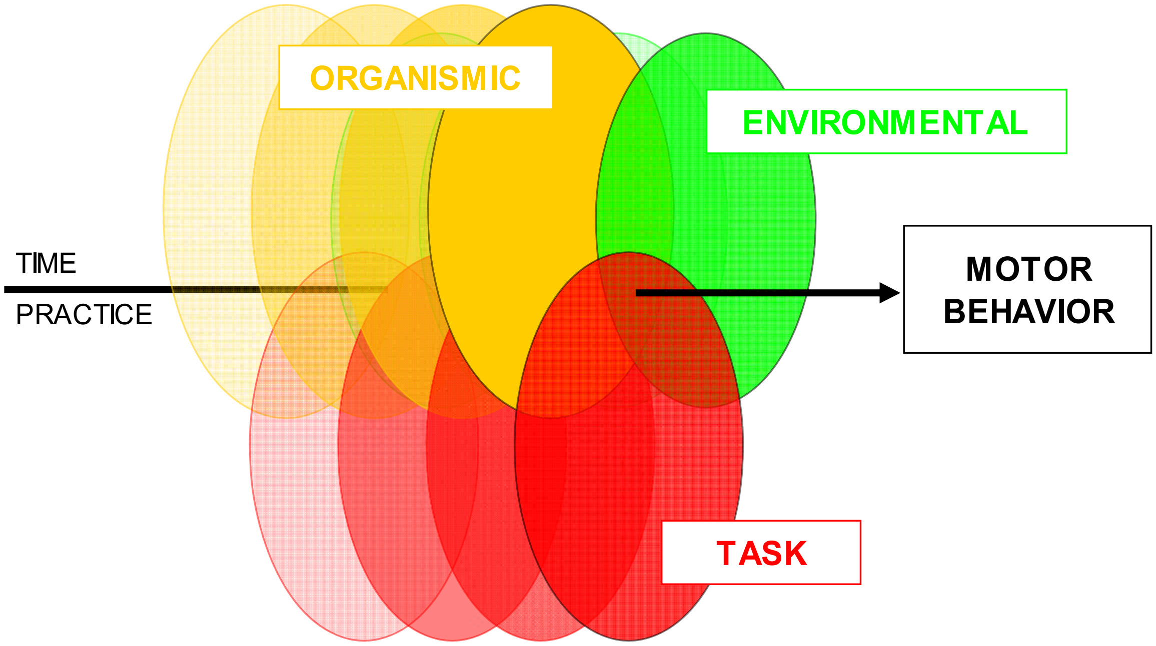

Fig. 3. Sketch of the emergence of motor behavior impacted by the constraints (organismic, task, and environmental) and practice.

The *task constraints* include the physical characteristics of the task at hand (implements, machines, etc.) and the instructions that are given to participants about their goal or the particular coordination they must perform. It is the requirements of the task at hand that ultimately shapes the movement that we see (Clark, 1995). Task difficulties create learning potential whose function differs according to the level of the performer, the complexity of the task, and the training environment (Guadagnoli & Lee, 2004). Task complexity has been defined as the number of movement segments that are involved (Brydges, Carnahan, Backstein, & Dubrowski, 2007), whereas task difficulty can be divided into (Brydges et al., 2007; Guadagnoli et al., 2004): (a) nominal task difficulty, which includes only the characteristics of the task, irrespective of the person performing it or the conditions under which the task is performed; and (b) functional task difficulty, which refers to how challenging the task is relative to the skill level of the individual performing the task and to the conditions under which it is being performed. Furthermore, comparing the skill learning of different tasks, swing in a ski simulator or in parallel bars, Teulier et al. (2006) proposed that the time rate to improve performance and coordination had been affected by both the tasks' difficulty and complexity.

The *environmental constraints* are defined by the physical environment (gravity, ambient temperature, etc.), as well as from the cultural environment, which tends to promote some kinds of action and to prohibit others. On earth, gravity is a key environmental constraint on movement performance for all tasks. The characteristics (friction, shape) of the apparatus where the task is performed as such as a bicycle, skate or high bar in gymnastics are also typically considered as environmental constraints. The DST offers an advantage over other theoretical approaches since it provides an explanation about changes occurred in movement including contextual analysis (Clark et al., 1993; Thelen et al., 1994).

Interaction flow between sub-systems and practice

Constraints may be considered subsystems relevant to the behavior and they are in continuous change. Constraints may be relatively time dependent or time independent, that is, their rate of change over time varies considerably with the level of analysis and parameter under construction (Newell, 1986). Similarly, sub-systems of the individual and their relationships can be modified across time, they are *dynamic systems*. These dynamic characteristics (influence of time on constraints and sub-systems) and constant interaction flow between sub-systems provide individuals with the capacity of continuous self-organization. The ‘instability’ generated by this interaction flow allows individuals to explore new modes of organization and coordination or to adapt them to the contextual demands (Kelso, Scholz, & Schöner, 1986).

The interaction flow between sub-systems during motor learning is highly affected by the practice. Indeed, practice is generally considered to be the single most important factor responsible for the permanent improvement in the ability to perform a motor skill (Guadagnoli et al., 2004; Nourrit et al., 2000). The highest level of skill performing a task (expert performing) required years of practice (Clark, 1995; Guadagnoli et al., 2004; Kami, 1996). Therefore, in dynamical system approach the acquisition of a motor skill is conceived as an emergent property from the complex interplay between practice and a set of interrelated constraints (or subsystems).

Transition from one motor behavior to another

Because constraints or subsystems are dynamic in nature, the behavior of an individual may change depending on the state (specific characteristics) of these constraints. Change from one motor behavior to another has been traditionally explained as a progressive phenomenon. However, studies have already shown that transitions between behaviors can be abrupt and clearly non-lineal. On the base of these processes of change one can observe *competition* between what an individual want or is instructed to perform and the natural tendency of the system to prefer some established motor behavior. On the other hand, several authors also following the DST (Delignières et al., *in press;* Thelen et al., 1994) suggested that new motor behavior is achieved with the cooperation between this new behavior and the previously acquired behaviors. Therefore, requirement to delete acquired behaviors or to compete between new and acquired behavior during learning is not necessary with the DST proposition. Individuals create a first version of the movement to fit task requisites, later another version of the movement emerges, and both versions of the movement will be combined in a second step of the learning process. Indeed, Nourrit et al. (2003) and Teulier et al. (2006) suggested that novices seemed to exploit their initial behavior to reach acceptable performance levels before they can engage in a new version of the behavior which includes true coordination change.

Discovering new modes of coordination may involve an individual undergoing a transition from one stable coordination mode to another (Handford et al., 1997; Temprado et al., 1997). Well learned behaviors show a ‘stable’ state that can be described as an attractor. Changes from one stable state to another occur when critical sub-systems (control parameters) progress in adequate amount to produce a qualitative change (bifurcation). That is, motor learning is a non-linear process and transition between coordination modes occurs abruptly rather than in progressive change (Nourrit, Delignières, Caillou, Deschamps, & Lauriot, 2003; van Emmerik, Rosenstein, McDermott, & Hamill, 2004). Stable forms of coordination show low variability and represent behavioral states that are reproducible and independent of each other. In contrast, high variability is characteristic of a system in transition (Clark et al., 1993; Clark, 1995; Hamill, van Emmerik, Heiderscheit, & Li, 1999).

Variability

Variability was traditionally interpreted as a problem or noise that must be minimized to achieve optimal performance at a given task. However, from a DST perspective, variability is seen as a functional index to assess necessary fluctuations to allow individual to learn new movement or to adapt learned movement to changing constraints from one situation to the next

(Barlett, Wheat, & Robins, 2007; Button, MacLeod, Sanders, & Coleman, 2003; Handford et al., 1997; Harbuorne & Stergiou, 2009; van Emmerik & van Wegen, 2000; Wilson, Simpson, van Emmerik, & Hamill, 2008). Movement variability is computed considering levels of analysis by inter-subject or within subject variability. Inter-subject variability can be used to check the impact of contextual demands on performance variability (Nourrit et al., 2000) or the relevance of critical events and functional phases of the movement to high level performance (Fleisig Chu, Weber, & Andrews, 2009; Koeing, Tamres, & Mann., 1994).

On the other hand, higher within subject variability of coordination in similar conditions could reveal transition phases in learning (Clark et al., 1993; Clark, 1995; Hamill et al., 1999). However, changes in the within subject variability were also observed when expertise level increases. In the early stages of learning variability is high due to both exploration of new modes of coordination and decreased practice (Buchanan, Zihlman, Ryu, & Wright, 2007; Robertson, 2001). In contrast, expert performers' variability can also be great to provide the flexibility to adapt movement to specific contexts (Davids, Glazier, Araújo, & Bartlett, 2003; Hamill et al, 1999; Wilson et al., 2008). It was suggested that within subject variability conforms to a U-shaped graph as a function of skill progression (Wilson et al., 2008). In addition, within subject variability can be analyzed as the variability between trials of the same individual (inter-trial variability) or as changes in coordination mode during the execution of the trial (intra-trial variability). These difference sources of within subject variability can aid in the interpretation of the dynamic state of the individual´s behavior.

Techniques and tools from Dynamical System Theory

As aforementioned, motor learning process changes abruptly (non-linear) and involves multiple sub-systems (complex system) impacted by the context and practice. It will be necessary techniques and tools that allow examine changes in the motor learning process while complexity of the system is brought down (Jensen, 2005). In order to reduce the complexity of the system, that is, from high-dimensionality to low-dimensionality, Thelen and Smith (1994) proposed that few parameters (essential variables) can be used to characterize motor behavior. In addition, identification and quantification of these essential variables show states of the system, stability or instability, describing dynamic process of motor learning (Temprado et al., 1997).

Techniques or tools choice to analyze motor learning relate to the power of the obtained variables to ask research questions. To explain changes in the motor behavior from a DST approach, detailed, valid and accurate data collection is necessary. Biomechanics offer great expectations to study motor learning, describing changes in the process of learning and providing information to understand this process (Winter & Eng, 1995; Jensen, 2005). Kinematics and kinetics of different movement were traditionally studied (for example locomotion by Eng & Winter, 1995; Foti, Davids, & Bagley, 2000; Prince, Corriveau, Hébert, & Winter, 1997) but reducing data techniques are necessary to understand motor learning. DST approach proposes several reducing data techniques from engineering, applied physics or biomechanics itself to be used in studies in biological and complex systems processes as human motor learning. These techniques and tools are well-matched with principles proposed by DST, and are capable to show generalities of the movement or singularities caused by individual or contextual differences.

Techniques and tools from DST help movement scientists to understand sources and processes of motor learning (Clark & Phillips, 1991; Mauerberg, Schuller, & Fantucci, 1994;

Mauerberg-deCastro & Angulo-Kinzler, 2000; Winstein & Garfinkel, 1989). Motor behavior can be abstracted to a graph representation which curve shapes are then analyzed qualitatively. Several studies in motor learning to identify the coordinative pattern of thigh, leg, and foot during human locomotion used these phase portraits (Clark et al., 1993; Holt & Jeng, 1992; Winstein et al., 1989). Phase portraits display segmental or joint velocity as a function of displacement. Coordination between limb segments or joints in gait were also analyzed by the continuous relative phase (Clark et al., 1993; Haddad, van Emmerik, Whittlesey, & Hamill, 2006; Li, van der Bogert, Caldwell, van Emmerik, & Hamill, 1999). Continuous relative phase is obtained calculating difference of the four-quadrant arctangent angle at every point of the movement cycle between two segments or joints. In contrast, few articles used these graphic tools to analyze sport skills learning (Button et al., 2003; Temprado et al., 1997).

Longswing on the high bar: sport skill under study

Learning sport skills represent an ideal situation to assess how individual learn a task in the two phases, facing a novel task and improving a learned task. However, given the big number of sport skills and motor learning specificity, it was necessary to select one task to study skill acquisition and fine tuning processes. We selected the longswing on the high bar in gymnastics as the focus of this study. The coaching literature identified the ‘regular’ or ‘traditional’ backward longswing on high bar as a fundamental basic skill, because of its association with the development of more complex high bar movements (Hiley & Yeadon, 2003; Irwin & Kerwin, 2005; Irwin et al., 2007b). Indeed, the majority of movements on the high bar belong to a group of rotations in the vertical plane around a horizontal axis (Brüggemann, Cheetham, Alp, & Arampatzis, 1994). Gymnasts learn how to perform the longswing from their first years of training, and they improve and adapt longswing across the years to achieve new skills on the high bar.

The aim of the ‘regular’ backward swing is to go from handstand to handstand position through rotation around the high bar with a straight body (Hiley et al., 2003). To understand the motor strategies of the individual underlying the execution of the longswing, it will be important to know the biomechanical characteristics of this movement. Considering the gymnast as a point of mass (located at the body center of mass, CM) rigidly attached to an axis of rotation (high bar) the swing on high bar can be contemplate as a forced pendulum (Sevrez, Berton, Rao, & Bootsma, 2009). During the ascending phase of the longswing, the angular momentum created during the downswing will be lost. Gymnasts modify their body configuration in order to create a positive balance between the angular momentum created during the downswing and the angular momentum lost in the ascending phase (Yeadon & Hiley, 2000). Changes in the body configuration lead to a change in the distance between the CM and the axis of rotation. The quality of this movement is defined by the Fédération Internationale de Gymnastique (FIG) Code of Points (2009) where arms and legs full extension during the whole movement is expected. Movements of the hip, shoulder, and trunk can be performed then to maintain the positive balance of the angular momentum.

Several studies documented the importance of the hip and shoulder flexion and extension for the successful execution of the swing (Arampatzis & Bruggemann, 1999; Hiley et al., 2003; Yeadon et al., 2000). Mechanically, the most important functional characteristics of the swing have been identified as (1) a rapid hyper-extension to flexion of the hip after the gymnast passes through the lowest part of the circle (Brüggemann et al., 1994; Hiley et al., 2003; Irwin & Kerwin, 2007a; Irwin et al., 2007b; Yeadon et al., 2000) and (2) a flexion to extension of the shoulder joint before the highest point of the circle (Hiley et al., 2003; Irwin et al., 2007a; Irwin et al., 2007b; Yeadon et al., 2000). Irwin and Kerwin (2005, 2007b) termed these phases of the hips and shoulders as the ‘functional phases’. In this way, the hip functional phase reduces the radius between the center of mass (CM) and the rotational axis to help in the maintenance of the angular momentum (Irwin et al., 2005; Irwin et al., 2007b; Yeadon et al., 2000), and the shoulder functional phase pushes up the CM over the bar to continue gaining potential energy.

Swing on the high bar has been investigated in previous research to evaluate its optimal kinematics and kinetics characteristics (Arampatzis et al., 1999; Gervais & Tally, 1993; Hiley et al., 2003; Kerwin, Yeadon, & Harwood, 1993; Kopp & Reid, 1980; Witten, Brown, Witten, & Wells, 1994; Yeadon et al., 2000). In addition, studies have compared swing progression exercises to achieve optimal skill performance (Irwin et al., 2005; Irwin et al., 2007a; Irwin et al., 2007b). However, the motor learning process has not been contemplated in previous studies about the high bar swing. Therefore, the overarching goal of this thesis is to characterize both periods of learning (skill acquisition and fine tuning process) from a dynamical system theory perspective focusing in the longswing as a sport skill.

Justification, structure, aims, and hypotheses

Numerous motor-perceptual tasks can be observed across the ages, especially if individuals are involved in sport activities. A person facing a novel task has to elaborate new movements to achieve the task goal (skill acquisition period). To become more successful and efficient, that is, to be an expert in a learned task, the subject must adjusts movement parameters depending on many constraints (fine tuning skill period) (Clark, 1995; Delignieres et al., 1998; Newell, 1991; Temprado et al., 1997). Learning movements in these sequential but overlapping periods is affected by both motor (performance and coordination) and perceptual factors (Nourrit et al., 2000; Walter, 1998; Whitall et al., 2006). Several authors have proposed that performance and coordination progress in parallel but with different time rate during the process of motor learning (Chow et al., 2007; Gentile, 1998; Hikosaka, et al., 2002; Hung et al., 2008; Teulier et al., 2006). However, these studies were conducted in short time scales (i.e. an average of 8.4 training sessions), performing simple tasks, and with relatively small difficulty to achieve the goal. In addition, few studies have been carried out addressing the transfer from motor learning to perceptual learning (Hecht et al., 2001). Taken together, it seems reasonable to examine the characteristics of the motor-perceptual learning process during a complex task (for example, a sport skill) including both periods: acquisition and fine tuning up to the expert level.

From a DST perspective, movement arises from the relative impact of practice and constraints (organismic, task, and environmental) (Clark, 1995; Clark, 2002; Handford et al., 1997; Holt, 2005; Kugler et al., 1980; Marin et al., 1999; Newell, 1986; Nourrit et al., 2000; Thelen et al., 1994). Focusing in the organismic constraints, the a-priory talent is a critical point for understanding motor learning in the skill acquisition period (Delignieres et al., 1998;

Swinnen et al., 2002). In addition, the age of the performer must be specially considered in the fine tuning skill period due to the biological maturational and expertise processes taking place with time (Gautier et al., 2009; Marin et al., 1999). If one wants to analyze the impact of the organismic constraints in movement learning, it will be necessary to hold task (including complexity and difficulty) and environmental constraints fixed

Another important postulate of DST is that motor learning is considered a non-linear process, that is, changes from one stable motor behavior to another motor behavior are abrupt. These transition phases can be identified by increases in variability in the motor factors (performance and coordination) (Clark et al., 1993; Clark, 1995; Hamill et al., 1999). Therefore, and according to the DST perspective, it seems reasonable to study the impact of the organismic constraints in the non-linear learning process examining changes in performance and coordination variability.

The longswing in gymnastics has been well-studied in previous research which focused on the optimization of its biomechanical parameters (kinematic and kinetic) (Kopp et al., 1980; Gervais et al., 1993; Kerwin et al., 1993; Witten et al., 1994; Arampatzis et al., 1999; Yeadon et al., 2000; Hiley et al., 2003). These studies about the longswing provide a mechanical understanding of the task, but they failed to address the learning questions. In fact, no studies were conducted to examine how this task is learned. The longswing in gymnastics can be utilized as a novel task because most individuals do not experience practice of gymnastics movements. On the other hand, the longswing is a fundamental basic skill which allows checking the process period of fine tuning the skill. In addition, the task and environmental constraints can be fixed during the longswing learning to focus on the impact of the organismic constraints.

Understanding how we learn to move (facing a novel task) and how we become experts (fine tuning process) are essential questions for those in educational, sport, and therapeutic settings where the goal of motor skillfulness is an important objective in and of itself (Clark, 1995). Most sports and exercise practitioners use models of human behavior, either implicitly or explicitly, as a basis for their educational activity with the intention to become more effective in their practice time (Handford et al., 1997). Research focused in learning process of the swing on a high bar may help practitioners to develop an appropriate model for understanding how learners acquire and modify motor skills, and in turn, practitioners can improve their intervention during their sessions.

This thesis is divided into 7 chapters, the first being this introduction to which it follows a sequence of five articles (Chapters 2-6). It ends with a general discussion and conclusions as the final chapter. As expected, limitations of the thesis and futures directions of research are also outlined in the final chapter.

Chapter 2. El retrato de fase como una herramienta de análisis del comportamiento motor (Understanding phase portrait as a tool for motor behavior analysis)

Dynamical Systems Theory (DST) contemplates learning from its contextual demands, individual differences, variability of the subject, and the non-linear characteristics of the process. DST used several tools from engineering, physics or biological sciences to understand sources and processes of movement learning (Clark & Phillips, 1991; Mauerberg, Schuller, & Fantucci, 1994; Mauerberg-deCastro & Angulo-Kinzler, 2000; Winstein & Garfinkel, 1989). Phase portraits were widely used to identify the coordinative pattern of thigh, leg, and foot during the human locomotion (Clark & Phillips, 1993; Holt & Jeng, 1992; Winstein & Garfinkel, 1989).

Modifications of the coordinative patterns during sport skill learning are less studied. It will be interesting to know if the phase portrait can be used to analyze sport skill in their natural context.

The aim of this article was to examine the suitability of phase portraits in analyzing sport skills. In this first article, we used data from a well-known skill (locomotion) and from a sport skill (swing in high bar) in different states of learning and situations to assess the suitability of the phase portrait to describe the motor behavior of the limbs or the joints. We hypothesize that the phase portrait will be also adequate to analyze the motor behavior of limbs or joints in a sport skill.

Chapter 3. El ángulo de fase y la fase relativa continua para la investigación de la coordinación motora (Phase angle and continuous relative phase in motor coordination research)

Spatial-temporal relationships among limb segments or joints (i.e. coordination) change in order to achieve or adapt movements. Indeed, the discovery an effective coordination is one of the main concerns of novice individual when faced with a novel task (Bernstein, 1967; Temprado, Della-Grasta, Farrell, & Laurent, 1997; Stergiou, Jensen, Bates, Scholten, & Tzetzis., 2001; Hong & Newell, 2006). Dynamical system perspective used the angle phase and the continuous relative phase (CRP) extensively to assess coordination in walking (Clark & Phillips, 1993; Haddad, van Emmerik, Whittlesey, & Hamill, 2006; Li, van der Bogert, Caldwell, van Emmerik, & Hamill, 1999), while few studies use these tools to examine learning in sport skills (Button, MacLeod, Sander, & Coleman, 2003; Temprado et al., 1997).

In order to assess whether the phase angle and CRP are appropriate to study coordination of two limbs or joints in sport skills, we design a methodological study where data from a well-known skill (locomotion) and a sport skill (swing in high bar) were used and interpreted. We hypothesize that the relative angle and the CRP will be adequate to detect changes in coordination during the learning of a sport skill.

Chapter 4. Swing high bar performance in novice adults: Effects of practice and talent

Studies addressing learning of a motor-perceptual task can be focused in the skill acquisition period (when the person is faced with a novel task), or in the fine tuning skill period (Clark, 1995; Delignieres et al., 1998; Newell, 1991; Temprado, Della-Grasta, Farrell, & Laurent, 1997). Skill acquisition will be highly impacted by the amount and quality of practice individuals may accumulate but also by their initial skill level (a-priori talent) (Delignieres et al., 1998; Swinnen & Carson, 2002). In addition, given that individual motor learning has been closely associated with perception of the environment (Hatzitaki, Zisi, Kollias, & Kioumourtzoglou, 2002), it's reasonable to expect a relationship between perceptual learning, accumulated practice and a-priori talent.

In this study we examine the performance and perceptual gains during longswing learning by novice participants under unique point view. That is, we assessed learning factors involved in the acquisition of this skill considering the a-priori talent of the individual and the practice effects. In addition, we evaluated their perceptual ability. A novice cohort was statistically classified in two groups (spontaneous-talented, ST, and non-spontaneous-talented, NST) on basis of their initial skill level. An expert group was also included for comparison purposes. The spontaneous-talented group was more similar to the expert group than the non-spontaneous-talented. Three aims were pursued in this study: (1) to describe movement performance changes after a two-month practice period of a novel task (swing on high bar) in novices, (2) to examine differential practice effects within the novice cohort considering initial level of performance (ST versus NST), and (3) to assess performance level perception in these same subjects before and after the practice period. In addition, post-practice performance of the novices was compared to expert gymnasts.

Improvements in the novice cohort due to practice were expected. However, within the novice cohort, those subjects with spontaneous talent for this task were hypothesized to experience larger improvements in performance than those less talented. Similarly, perception of performance level will be closer to objective estimates in those subjects with spontaneous talent after the practice period. In addition, it was hypothesized that improvements in performance will be revealed by the closer adjustment in the novice group to the events and path of the expert gymnasts' hip and shoulder functional phases.

Chapter 5. Coordination analysis reveals differences in performance strategies for the swing high bar in novice adults

Skill acquisition can be described by measurable outcomes of the movement (performance) and by relationships between segments or joints involved in the movement (coordination) (Delignières et al., in press; Vereijeken et al., 1997). Bernstein (1967) suggested examining coordination to gain a better insight of the learning process. In addition, he stressed the importance to assess variability. Others have supported this view given that learning is a non-linear process characterized by abrupt transition phases (Nourrit, Delignières, Caillou, Deschamps, and Lauriot, 2003; van Emmerik, Rosenstein, McDermott, & Hamill, 2004) which could be revealed by the higher within subject variability of coordination (Clark et al., 1993; Clark, 1995; Hamill et al., 1999). On the other hand, it is important to note that adoption of a coordination mode and changes in variability due to practice could be impacted by the individual a-priori talent.

The aim of this study was to describe movement coordination changes and variability after a two-month practice period of a novel task (swing on the high bar) in a novice cohort, which was divided in two groups considering the initial level of performance and similarity with an expert group (spontaneous-talented, ST, and non-spontaneous-talented, NST). In addition, post-practice performance, coordination and coordination variability of the novices were compared to expert gymnasts. We expected that that ST group would experience larger improvements in performance and coordination than the NST group. Concretely, we hypothesized that swing amplitude would be larger while hip and shoulder movements would be more consistent and better coordinated in the ST group than the NST group. Additionally, we also expected novices' performance and coordination would improve with practice making their swing more similar to experts' swing.

Chapter 6. Skill acquisition of the swing in high bar gymnastics across age

As we mention above, two periods in movement learning process have been identified in the scientific literature: skill acquisition and fine tuning skill (Clark, 1995; Delignieres et al., 1998; Newell, 1991; Temprado, Della-Grasta, Farrell, & Laurent, 1997). During the fine tuning skill period the motor learning process could be impacted by two other processes. First, the individual level of development as a biological maturation, and second the accumulation of expertise capabilities of the individual (Gautier, Marin, Leroy, & Thouvarecq, 2009; Marin et al., 1999). While chapter 4 and 5 focused in the skill acquisition period considering the a-priori talent, this current study examined longswing performance and coordination as a fine tuning skill period utilizing competition age groups (from beginners to experts) as a natural occurrence of such learning period. Each competition age group was composed by trained gymnasts with extensive practice of the task but of different ages. The comparison of different age groups could help us to identify the effects of the organismic properties (development and expertise level) on performance and coordination dynamics (Gautier et al., 2009). In addition, comparing different age groups allows access to observe relevant long-term changes than a study with a reduced age range (Gautier et al., 2009; Temprado et al., 1997).

Two principal aims were pursued in this study. First, to determine whether the competitive age groups use different performance and coordination modes to increase the swing amplitude or achieve the complete longswing (from handstand to handstand). It was hypothesized that performance and coordination would become more similar to the older age group of gymnasts (experts) as a function of completion age group. Given the different time rate between performance and coordination during motor learning (Chow, Davids, Button, & Koh, 2007; Gentile, 1998; Hisosaka, Nakamura, Sakai, & Nakahara, 2002; Hung, Kaminski, Fineman, Monroe, & Gentile, 2008; Teulier, Nourrit, & Delignières, 2006), we expected that ‘expert’ performance including the spatial sequences of the movement will be acquired by the younger gymnasts while the ‘expert’ modes of coordination would be acquired by the intermediate competition age groups.

The second aim of the study was to assess changes in the within subject variability of the performance and coordination across the competition age groups. We hypothesize that within subject variability of the performance and coordination would be larger for the younger competition age groups than the intermediate groups, but this within subject variability would increase again in the older group. In order to support the findings of Wilson et al. (2008) that examined the within subject variability as a function of skill progression and suggested that line of this function conform a U-shaped graph, we analyzed the U-shaped fit of the within subject variability performing longswing across the competition age groups.

Chapter 2. El retrato de fase como una herramienta de análisis del comportamiento motor (Understanding phase portrait as a tool for motor behavior analysis)

Apunts. Educación Física y Deporte (in press)

TÍTULO:

EL RETRATO DE FASE COMO UNA HERRAMIENTA DE ANÁLISIS DEL COMPORTAMIENTO MOTOR

TITLE:

UNDERSTANDING PHASE PORTRAITS AS A TOOL FOR MOTOR BEHAVIOR ANALYSIS

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EL RETRATO DE FASE COMO UNA HERRAMIENTA DE ANÁLISIS DEL COMPORTAMIENTO MOTOR

Resumen

Existe gran número de investigaciones centradas en la adquisición y perfeccionamiento de habilidades motrices. . Estas investigaciones intentan explicar cuál es la fuente y los procesos de cambio de los comportamientos motores que permiten al individuo adquirir o perfeccionar una habilidad. La ventaja de la Teoría de los Sistemas Dinámicos (TSD) como marco de referencia es la inclusión de un análisis contextual en el proceso de aprendizaje. El objetivo de este artículo es dar a conocer una metodología llamada retrato de fase la cual facilita el estudio del comportamiento motor basándose en los principios de la TSD. Datos biomecánicos tratados con una técnica de reducción adecuada constituyen una buena herramienta para describir y entender los cambios que suceden en el comportamiento motor. Los retratos de fase, mediante un gráfico (posición angular, velocidad angular), son capaces de capturar el complejo juego de fuerzas que influyen en el comportamiento motor. En este artículo, las formas de las trayectorias de los gráficos nos indicaron: (1) cómo el organismo se comporta durante la realización de las habilidades motoras analizadas mostrando sus patrones generales; (2) las singularidades poblacionales (con deficiencias y sin deficiencias) o individuales; (3) los comportamientos adquiridos en el proceso de aprendizaje (novato y experto); y (4) los cambios producidos por manipulación del entorno. No obstante, los retratos de fase aunque muy útiles para resumir el comportamiento motor, no son representaciones completas del mismo y deberíamos completarlos con otras técnicas de análisis.

PALABRAS CLAVE: Aprendizaje motor, Biomecánica, Teoría de los sistemas dinámicos, Locomoción, Habilidades deportivas.

UNDERSTANDING PHASE PORTRAITS AS A TOOL FOR MOTOR BEHAVIOR ANALYSIS

Abstract

Currently, great number of investigations focuses on the acquisition and improvement of motor skills. These studies address the emergence of new motor behaviors including the processes of change to acquire and improve new skills. The advantage of using the Dynamic System Theory (DST) framework is the inclusion of contextual analysis to understand the learning process. The objective of this article is to present a methodology to study motor behavior based on the principles of the DST. Biomechanic data treated with the appropriate reduction technique constitute a good tool to describe and understand changes in motor behavior. The phase portraits are capable through a graph (angular position, angular velocity) to capture the complex relationship of forces that affect the motor behavior. The shape graph’s trajectory shape indicated to us: (1) how the organism behaves during the analyzed motor skills and show its general pattern; (2) to discern the population singularities (with disabilities and without disabilities) or individual singularities; (3) the different behaviors acquired in the learning process (novice and expert); and (4) the changes due to manipulation of the environment. Nevertheless, the phase portraits although very useful to summarize the motor behaviour, are not complete representations of these skills and we should complete them with other analysis techniques.

KEYWORDS: Motor learning, Biomechanics, Dynamic system theory, Locomotion, Sport skills

INTRODUCCIÓN

A lo largo de la vida surgen, se desarrollan e incluso desaparecen comportamientos motrices. Estos comportamientos están vinculados a movimientos con objetivos concretos, es decir, se relacionan con tareas. Cuando la producción de una tarea permite resolver un problema motriz alcanzando las máximas expectativas de éxito y con un mínimo de tiempo y energía, estamos hablando de habilidad (Riera, 2005). Precisamente, una de las preguntas que centran actualmente las investigaciones y debates teóricos recae en cuál es la fuente de los nuevos comportamientos motores y como estos pasan a ser movimientos hábiles (Jensen, 2005).

Durante las últimas décadas del siglo XX han predominado dos teorías sobre el aprendizaje motor: las teorías de maduración neural y las teorías cognitivas. Según las teorías de maduración neural la habilidad llega desde las estructuras jerárquicas del sistema nervioso central (SNC), llamadas generadores centrales de patrones, que producen la secuencia y ritmo de la activación muscular (Clark y Phillips, 1993). Así, el comportamiento es preescrito o predeterminado por la maduración del SNC, lo que implicaría que los otros subsistemas del individuo (dimensiones antropométricas, por ejemplo) y sus relaciones no tienen influencia en el desarrollo de los comportamientos motores. La perspectiva cognitiva entiende que el aprendizaje viene principalmente determinado por representaciones internas previas al movimiento y por los programas motores generalizados a disposición del individuo (Schmidt, 1982). De esta forma el comportamiento es producido por la formación de un esquema motor enfatizado a través de la experimentación.

Ambas teorías, la madurativa y la cognitiva, ignoran la riqueza en el desarrollo de los comportamientos que surgen desde los diversos subsistemas y sus procesos (Thelen y Ulrich, 1991). Estos puntos de vista puede ser concebibles cuando la tarea a realizar constituye una variante de una previamente aprendida, pero son menos fáciles de aplicar cuando el comportamiento de un sujeto se encuentra delante de una tarea completamente nueva (Delignieres et al., 1998). Además, muchas técnicas para el análisis del comportamiento motor fueron aplicadas solamente para describir el comportamiento en lugar de explicar el proceso de elaboración, organización y adaptación del comportamiento motor. Así, la efectividad del control y el progreso del aprendizaje sólo se evaluaban respecto del total de la actuación (Temprado, Della-Grasta, Farrell, y Laurent, 1997).

Por otro lado, es aceptado que el individuo está formado de múltiples sistemas que interactúan y que dichos sistemas son abiertos, es decir, modifican sus comportamientos bajo la influencia de otros sistemas o de la situación. Una explicación teórica alternativa a la madurativa y la cognitiva que se ha estado desarrollando sobre las últimas décadas es la Teoría de los Sistemas Dinámicos (TSD). La TSD ve el movimiento como un comportamiento emergente que surge desde la dinámica colectiva de todos los subsistemas del organismo que están implicados en la tarea. Entre otros podemos citar: el estatus neural, las características biomecánicas, la experiencia, el nivel de alerta y la precisión visual (Thelen et al., 1991; Kugler, Kelso, y Turvey, 1982). Los principales factores que condicionan la forma específica del comportamiento motor, los llamados "*constraints*" en la literatura inglesa, se categorizan en pertenecientes al entorno, a la tarea o al organismo (Newell, 1986; Clark et al., 1993). Los condicionantes del entorno provienen del entorno físico (gravedad, temperatura ambiental, etc.), así como del entorno cultural, los cuales tienen tendencia a promover cierto tipo de movimiento y a desterrar otros. Los condicionantes de la tarea incluyen las características físicas de la tarea en si misma (implementos, máquinas, etc.) y las instrucciones que se da a los ejecutantes sobre el objetivo o de la coordinación particular que deben realizar. Por ultimo, los condicionantes del organismo incluyen las características físicas del ejecutante (el peso, la altura y la forma del cuerpo, por ejemplo) y sus atributos fisiológicos y psicológicos. El impacto relativo de estas tres categorías de condicionantes en el comportamiento motor se modifica de acuerdo a las circunstancias específicas. Además, la TSD establece que los sistemas y sus relaciones se modifican en el tiempo, son “*sistemas dinámicos*”. Dichas propiedades dinámicas dan al sistema la capacidad de continua auto-organización gracias a la constante fluctuación que existe entre las interacciones de los subsistemas. La fluctuación de las interacciones, provocada por los cambios de los mismos subsistemas y/o de sus condicionantes, hace que los cambios puedan emerger resultando en un nuevo movimiento o modificando un movimiento ya aprendido.

El aprendizaje, por lo tanto, puede ser considerado como una modificación de la dinámica de los subsistemas del comportamiento motor. La ventaja de utilizar la TSD para enmarcar el aprendizaje motor reside en el hecho que podemos proponer una explicación orientada al proceso, que busca explicar los cambios, e incluye un análisis de las circunstancias en que se desarrolla (Clark et al., 1993; Thelen y Smith, 1994). Tradicionalmente, el cambio de un comportamiento a otro se ha presentado como un fenómeno progresivo, pero los estudios ya han demostrado que estas transiciones pueden ser abruptas y claramente no-lineales. En la base de estos procesos de cambio reside la *competición* entre lo que el ejecutante quiere o es instruido a hacer (tarea) y la tendencia natural del sistema a preferir ciertos comportamientos motores ya establecidos. Por otro lado, autores seguidores de la TSD (Thelen y Smith, 1994; Delignières, Teulier y Nourrit, *in press*) proponen que el surgimiento de un comportamiento motor experto se adquiere con la cooperación entre comportamientos nuevos y los ya adquiridos, sin la necesidad de desaprender un comportamiento o competir entre ellos. Así, el individuo hace una primera adaptación del comportamiento motor para satisfacer los requisitos de la tarea, y posteriormente aparece una segunda fase donde el comportamiento motor anterior se va alternando con la coordinación adquirida previamente.

Los cambios en los comportamientos motores suceden cuando subsistemas críticos (llamados parámetros de control) progresan lo suficiente como para generar un punto de transición que provoca un cambio cualitativo (bifurcación) y permite el surgimiento de un nuevo patrón (nueva organización). Los comportamientos motores en un determinado instante de la vida del sistema son definidos como estados atractores, los cuales exhiben una mayor o menor estabilidad. La inestabilidad del sistema permite al sistema explorar nuevas organizaciones y consecuentemente, nuevas soluciones motoras (Kelso, Scholz, y Schöner, 1986). Todos los sistemas dinámicos, aunque estables, siempre sufren algún tipo de fluctuación.

Como hemos dicho, el aprendizaje de una tarea es un proceso no-lineal que implica diversos subsistemas y el contexto donde se realizan. A causa de la complejidad en las relaciones que existen entre los subsistemas humanos para realizar los movimientos, nos encontramos con varias limitaciones cuando queremos analizar el comportamiento motor. Es por lo tanto necesaria una aproximación científica que deshaga la complejidad o multidimensionalidad de los comportamientos motores para entender los cambios que se presentan con el aprendizaje (Jensen, 2005). Los principios y herramientas de la TSD pueden ayudar a entender los orígenes y formas de los comportamientos motores, y las razones del cambio de sus patrones (Clark y Phillips, 1991; Mauerberg, Schuller, y Fantucci, 1994; Mauerberg-deCastro y Angulo-Kinzler, 2000; Winstein y Garfinkel, 1989). Así, el principal objetivo de este artículo es proporcionar a los lectores una metodología para el estudio del comportamiento motor basada en los principios de la TSD llamada retrato de fase. Esta metodología permitirá al investigador analizar los cambios del comportamiento motor de un segmento y/o articulación durante el proceso de adquisición o perfeccionamiento de una habilidad. Para ejemplificar la aplicabilidad de la metodología presentada e identificar sus ventajas y limitaciones, también se presentan varias habilidades motrices analizadas en nuestros laboratorios con dicha metodología.

HERRAMIENTAS UTILIZADAS POR LA TSD PARA EL ANÁLISIS DEL COMPORTAMIENTO MOTOR

Uno de los cambios más importantes en las ciencias del desarrollo y aprendizaje es la minuciosa captación, validez y precisión de los datos que reflejan la actividad. La elección de la técnica o herramienta para analizar un fenómeno depende de la potencia de las variables que se obtendrán para dar respuestas a las cuestiones planteadas. La biomecánica nos presenta uno de los mejores campos científicos para el estudio de los comportamiento motores, no sólo para describir los cambios que suceden, sino también para entender porque los cambios pasan (Winter y Eng, 1995; Jensen, 2005). Tradicionalmente la biomecánica ha sido aplicada para describir el comportamiento motor sin explicar el proceso de emergencia y adquisición de las habilidades motrices. Así, parámetros de cinemática y cinética de la locomoción (Eng y Winter, 1995; Foti, Davids y Bagley, 2000; Prince, Corriveau, Hébert y Winter, 1997) o de diferentes habilidades deportivas (Arampatzis et al., 1999; Hiley et al., 2003; en el balanceo en barra fija, por ejemplo) son frecuentemente investigados con el propósito de cuantificar el comportamiento. Para realmente analizar el proceso de cambio de los comportamientos motores es necesario que estos conceptos biomecánicos sean combinados con técnicas de reducción de datos, con las que conseguiremos representar, resumir y explicar el comportamiento motor sin perder su contextualización.

Varias técnicas de reducción de datos del campo de la ingeniería, física aplicada, o la misma biomecánica vienen siendo aplicadas en el estudio de los sistemas biológicos complejos, en particular al comportamiento motor humano. Al asumir la TSD como marco referencial de nuestras investigaciones experimentales, la elección de las técnicas de reducción de datos a utilizar debe ser compatible con los principios propuestos por dicha aproximación. Por otro lado, las herramientas utilizadas deben ser capaces de mostrar las generalidades que exhibe un comportamiento motor debido a las propiedades comunes dentro de cada población, además de mostrar su singularidad a causa de sus características individuales. Por ejemplo, las características diferenciadas dentro del sistema nervioso central (SNC) de individuos portadores de parálisis cerebral "fuerzan" a una organización o cooperación diferente entre los subsistemas, resultando en un comportamiento motor singular. Así, los procesos de adaptación de algunas poblaciones portadoras de deficiencias están asociados con reglas de cooperación diferenciadas de aquellas observadas en poblaciones no portadoras de deficiencias. En el análisis de los comportamientos motores de los individuos portadores de parálisis cerebral, las herramientas de reducción correctamente seleccionadas mostrarán patrones similares a la población no portadora de deficiencias debido a las características que compartimos todos los humanos y las características de la tarea. A la vez, estas técnicas de reducción de datos pondrán de relieve las adaptaciones que la población portadora de deficiencias realiza en el patrón del comportamiento motor de dicha tarea.

Además de las diferencias causadas por los condicionantes del organismo, los comportamientos motores pueden surgir o modificarse para servir a un propósito (condicionantes de la tarea) y su constancia puede ser o no preservada en un amplio rango de demandas cambiantes del entorno (condicionantes del entorno). Por ejemplo, podemos andar a distintas velocidades y sobre terrenos diversos mientras mantenemos aún el "andar". El mantenimiento del comportamiento motor sobre estos cambios permite adaptaciones de los mismos comportamientos más que reorganizaciones y creación de nuevos comportamientos (Clark et al., 1993). Las herramientas de análisis elegidas han de facilitar también la observación de las adaptaciones del comportamiento al entorno.

Todo sistema muestra cierto grado de fluctuación que le permite adaptar el movimiento o crear uno nuevo. A pesar de esta fluctuación inherente, los comportamientos establecidos presentan un estado estable. Los estados de transición de un sistema inestable a un sistema estable, o viceversa, son característico de los procesos de aprendizaje. Las herramientas seleccionadas han de mostrar las fluctuaciones que permiten al sistema ser flexible y estable al mismo tiempo. En los puntos de transición, estas fluctuaciones intrínsecas aumentan y con ellas aumentan la variabilidad del comportamiento colectivo.

Para ser capaces de analizar el comportamiento motor es necesario poder reducir la complejidad del sistema, alta-dimensionalidad, a una baja-dimensionalidad. Thelen y Smith (1994) propone que unos pocos parámetros (variables esenciales) pueden caracterizar el funcionamiento del comportamiento motor por una simplificación de sus dimensiones y, además, estos pueden ser abstraídos en representaciones gráficas. La identificación de la variable esencial y de su valor permite la identificación de los distintos estados del sistema, estables o inestables, que constituyen la dinámica del comportamiento motor (Temprado et al., 1997).

EL RETRATO DE FASE ("PHASE PORTRAIT") COMO TÉCNICA DE ANÁLISIS DEL COMPORTAMIENTO MOTOR

Elaboración de los retratos de fase

Para entender mejor la baja-dimensionalidad, u organización fundamental de un sistema, podemos utilizar representaciones geométricas como los gráficos de retratos de fase. Los retratos de fase capturan el juego complejo de fuerzas activas y pasivas que se producen en un movimiento a través de un gráfico. Así, los retratos de fase son una descripción resumida de las interrelaciones del sistema y el surgimiento de la auto-organización del comportamiento motor. El gráfico del retrato de fase representa los *cambios* en la cinemática (posición angular versus velocidad angular) dentro de una región específica del sistema de coordenadas, región referida aquí como espacio del estado (*“state space”*) (Abraham y Shaw, 1984). A continuación se presentan las ecuaciones utilizadas para la realización de un gráfico de retrato de fase (Kurz y Stergiou, 2002; Kurz y Stergiou, 2004; Mauerberg-deCastro y Angulo-Kinzler, 2001):

1. Primero, el desplazamiento angular es normalizado.

$$\Theta i = \left(\frac{2 \times [\Theta i - \min(\Theta i)]}{\max(\Theta i) - \min(\Theta i)} \right) - 1$$

Donde Θ (grados) son los ángulos del recorrido articular

2. A continuación, la velocidad angular es normalizada. La velocidad angular igual a cero ha de corresponder a una velocidad angular normalizada igual a cero.

$$\dot{\omega} i = \frac{\omega i}{\max(\omega \mathrm{i})}$$

Donde ω (grados/segundos) son la velocidad angular del recorrido articular

3. Graficar en el eje de ordenadas *y* la velocidad angular (ω) y en el eje de abscisas *x* el ángulo (Θ)

Interpretación de los retratos de fase.

Para Thelen y Smith (1994) la convergencia de las órbitas de un sistema en una región dentro del espacio del estado caracteriza un atractor. Un atractor, representado por el retrato de fase, es una característica de preferencia de organización para el sistema. Los retratos de fase frecuentemente son interpretados de forma cualitativa (Mauerberg-deCastro et al., 2000; Winstein et al., 1989). La forma asumida por la trayectoria del atractor nos da una idea de cómo el organismo se comporta al verse afectado por las distintas restricciones. Los investigadores pueden visualizar patrones comunes en los retratos de fase, así como las diferentes estrategias adoptadas por los sistemas e identificar y definir los mecanismos de control. A continuación presentamos unas pautas para interpretar las formas que adquiere el retrato de fase durante el comportamiento motor una articulación o segmento (Winstein et al., 1989; Kurz et al., 2004; Mauerberg-deCastro et al., 2001) (Tabla 1).

TABLA 1

Estabilidad y variabilidad del comportamiento motor

El atractor muestra una preferencia (predisposición a una configuración) que no siempre puede ser cambiada con facilidad. Por ejemplo, las configuraciones del movimiento como las de la locomoción son atractores de tanta fuerza y estabilidad que perturbaciones incluso drásticas no les afecta. Al contrario muchas habilidades deportivas son fácilmente desestabilizadas por manipulaciones contextuales, falta de práctica o falta de atención. Los comportamientos cíclicos, como la marcha o los molinos en la barra, son marcados por la repetición dentro de una órbita cerrada del espacio del estado. La repetición de las trayectorias de los retratos de fase que caracterizan la estabilidad del patrón puede sufrir pequeñas perturbaciones a causa de la dinámica típica de los sistemas abiertos. Estas variaciones, observables en el gráfico como pequeños cambios de tamaño o de forma, que no afectan el patrón general confirman la flexibilidad del sistema (Fig. 1a durante la carrera y Fig. 1b durante el molino en barra fija de gimnasia). Por otra parte, la extrema rigidez en el comportamiento, marcada por una repetición con poca variabilidad, es una evidencia de falta de flexibilidad o extremo control en la ejecución del movimiento observable durante el proceso de aprendizaje (Fig. 1c en la marcha y Fig. 1d en el molino de barra fija). Similarmente, la extrema irregularidad en las trayectorias son una señal de inestabilidad (Fig. 1e en la marcha y Fig. 1f en el molino de barra fija).

FIGURA 1

Como hemos explicado antes, la tarea (caminar, molino en la barra), la situación del entorno (suelo o barra de equilibrio) y las condiciones del organismo (presencia de un síndrome o patología cerebral) son factores importantes para justificar la estabilidad/inestabilidad del comportamiento. Tanto los niños portadores como no-portadores de deficiencias pueden adquirir patrones de comportamiento estables. En el proceso de análisis en los cambios de estos comportamientos la variabilidad y la especificidad son aspectos importantes a tener en cuenta. La Fig. 2 presenta el proceso de aprendizaje de la marcha de un niño con síndrome de Down durante 8 meses de práctica (a, c y e) y de un balanceo en barra fija por gimnastas con distinto experiencia (b, d y f). Inicialmente las trayectorias para cada ciclo son distintas y el patrón no se percibe, pero con la práctica la forma trazada por el retrato de fase en cada ciclo se asemeja y emerge un patrón que será similar al del adulto o experto (ver Fig. 2).

FIGURA 2

Eficiencia mecánica del comportamiento motor

Otro aspecto importante durante el surgimiento y perfeccionamiento de un comportamiento motor se relaciona con la eficiencia del movimiento. La disipación de energía durante el movimiento como un proceso de gasto de energía, y con ello la eficiencia mecánica, puede ser visualizada en los retratos de fase basándonos en las inflexiones (cambios rápidos de velocidad) y expansiones de las trayectorias (el tamaño del atractor como producto de la relación entre el desplazamiento y la velocidad). Mucha de la energía gastada es generalmente resultado de los cambios de velocidad, como podemos ver en la Figura 3a y 3b el gasto de energía se vincularía a un movimiento amplio y más lento con mayor desplazamiento.

Las expansiones de las trayectorias se visualizan como una mayor área del espacio de estado indicando un mayor gasto energético. Aunque si los retratos de fase son normalizados podemos encontrarnos que el área aumente o disminuya perdiendo su tamaño original. A pesar de esta limitación la normalización nos permite comparar retratos de fase de diferentes sujetos o en diferentes contextos. Un ejemplo donde se producen estas diferencias entre el tamaño del retrato de fase normalizado y no normalizado es la Figura 3c. En esta figura un bebé exhibe pequeños pasos en la cinta rodante probablemente debido a las sensaciones (cosquillas o irritación en la planta del pie) causadas por las protuberancias de goma añadidas sobre la cinta. Esta manipulación del entorno probablemente hace que el bebé opte por no ampliar el paso, de esta forma no aumenta la presión de la planta del pie sobre una superficie desagradable para él. Si observásemos el retrato de fase sin normalizar el área ocupada, y con ello el gasto energético implicado, seria muy pequeña. Al contrario, el área ocupada se expande una vez normalizados el desplazamiento y la velocidad angular no por ello implicando un mayor gasto energético (Fig. 3c). Lo mismo sucede en la Figura 3d, donde se observa el comportamiento motor de la cadera durante los balanceos de poca amplitud de un niño gimnasta de poca experiencia.

En las Figuras 3e y 3g, se puede observar como dos niños portadores del síndrome de Down tienen similares disipaciones de energía en dos tareas, correr en el suelo y caminar en un trampolín respectivamente. En el primer caso la impulsión generada en la carrera hace al atractor expandir gradualmente su trayectoria, mientras que al caminar en el trampolín la elasticidad de la lona elástica genera el impulso (inclinación mostrada en la parte inferior de la gráfica). Además, en este último caso donde el niño se somete a la acción de las fuerzas pasivas y elásticas de la superficie, podemos ver como estas fuerzas dificultan el control del movimiento, lo cual queda reflejado en la variabilidad de las inflexiones que se presentan en la parte derecha e inferior de la gráfica. Ambas situaciones exhiben grandes cantidades de energía. Las Figuras 3f y 3h corresponden a la realización por parte de dos niños gimnastas de varios balanceos completos en la barra fija. En el primer caso se aprecia una parte inferior de la curva más plana, lo que indica un menor aprovechamiento de la fuerza de la gravedad y de los momentos de inercia.

FIGURA 3

Adaptaciones del comportamiento motor

Los distintos procesos o adaptaciones de los comportamientos motores pueden ser analizados simplemente visualizándose las formas del retrato de fase bajo restricciones ambientales y biológicas. En la Figura 4, columna de la izquierda, cada bebé exhibe un patrón único de movimiento de la marcha sobre una cinta rodante. Así, en la Figura 4a, donde el bebé camina en condiciones naturales, se observa una trayectoria que se inicia con una velocidad constante (meseta en la parte superior del gráfico) y que posteriormente desacelera causando la formación de una esquina (forma cuadrada en el atractor). En la Figura 4c se presenta el comportamiento motor de un bebé que está caminando sobre una superficie de velcro colocado sobre la cinta y en la planta del bebé con un calcetín. Las fuerzas elásticas del segmento y las características de la superficie son probablemente responsables del movimiento balístico que marca el inicio de la trayectoria (forma cuadrada en el atractor). A continuación, gradualmente sucede una desaceleración de la pierna en la mitad de la fase de balanceo de la marcha (parte superior de la gráfica) y reasumiendo un poco de velocidad angular al final de la misma fase de balanceo. Las Figuras 4e y 4g pertenecen a dos bebes caminando sobre una cinta rodante con protuberancias de goma. En el primer caso la fase de balanceo de la marcha es claramente pendular, no obstante, en la fase de apoyo (parte inferior de la gráfica) la trayectoria es plana y sin ganancia de velocidad angular, implicando una participación muscular de control del movimiento para estabilizar el muslo. En el segundo caso, el movimiento errático de la pierna en la fase de balanceo marca los dos bucles en la trayectoria del retrato de fase que sugieren reversiones del movimiento y por lo tanto falta de control.

Por otro lado, en la columna de la derecha podemos observar como sucede lo mismo con jóvenes adultos que adquieren una nueva habilidad deportiva concreta: el molino en la barra fija. En la Figura 4b, el participante iniciaba el movimiento con una meseta debido a la velocidad constante de la abertura de la cadera. En la figura 4d quedan reflejadas las acciones balísticas (inflexiones en la trayectoria del retrato de fase) que otro joven adulto en fase de aprendizaje realiza para intentar ganar amplitud de balanceo. La Figura 4f muestra una fase claramente pendular en la fase intermedia del movimiento, en cambio en las fase iniciales y finales la trayectoria es plana implicando una mayor implicación del control muscular. Y el último caso, Figura 4h, pertenece a un movimiento errático que realiza varios bucles en la trayectoria del retrato de fase sugiriendo reversiones del movimiento

FIGURA 4

Limitaciones de los retratos de fase

Los investigadores han de tener en cuenta que los retratos de fase, como todas las herramientas de análisis, tienen sus limitaciones. En primer lugar, el aspecto temporal se pierde porqué los parámetros de las coordenadas (posición angular y velocidad angular) son ambos representados independientemente del tiempo. Aunque, indirectamente se podría observar el distanciamiento entre los puntos graficados en la curva y estimar el tiempo en función de la frecuencia de muestreo de los datos recogidos. Esta ausencia de tiempo no permite verificar su coordinación con los otros segmentos o articulaciones. Para el análisis de las coordinaciones que se producen en la adquisición o perfeccionamiento de las habilidades motrices tendríamos que recurrir a otras herramientas de la TSD como el ángulo de fase y la fase relativa continua (Clark et al., 1993; Kurz et al., 2002; Kurz et al., 2004).

El análisis también puede estar limitado porque los retratos de fase sean representaciones bidimensionales de un sistema que en realidad se comporta tridimensionalmente. Además, según el tipo de tarea que se analiza se suele dar preferencia a evaluar los planos de movimiento donde se suceden los movimientos más importantes, como el sagital en el caso de la locomoción o el balanceo en barra fija. Pero no debemos olvidar que las actividades en los diferentes planos de movimiento son importantes cuando se trata de niños portadores de alguna deficiencia o cuando se trata de patrones que aún están emergiendo (como es el caso del aprendizaje del balanceo). Aunque el plano frontal en la locomoción y el balanceo sea de menor importancia, en sistemas inmaduros y atípicos pueden mostrar detalles de cómo los sujetos controlan y reducen los movimientos.

Otra limitación del uso de esta técnica es su interpretación. Una interpretación del retrato de fase, debido a su naturaleza cualitativa, acaba por sufrir ambigüedades causadas por el subjetivismo del investigador al hacer el análisis. Por ejemplo, ¿cuando se decide si el control del movimiento es pendular o balístico? No existen límites claros y objetivos en esta decisión. Además, como cualquier sistema abierto, el surgimiento de un comportamiento motor suele ser errático y estos comportamientos erráticos son más difíciles de ser descritos. Para facilitar la interpretación de los retratos de fase y eliminar cierto grado de subjetividad se suelen complementar los estudios con el análisis de variables cuantitativas, como por ejemplo el ratio [perímetro/(area$^{1/2}$)] o el análisis elíptico de Fourier (Polk, Spencer-Smith, DiBerardino, Ellis, Downen y Rosengren, 2008).

Por último, también ha de considerarse que según Kurz y Stergiou (2002, 2004) la normalización de los datos tiende a distorsionar la dinámica del comportamiento ya que la utilización de dos factores escalares distintos cambia el aspecto de los retratos de fase (el desplazamiento angular encaja en un rango de ±1 y la velocidad angular se escala mediante su máximo). Una pérdida del aspecto del ratio de los retratos de fase podría cambiar el comportamiento no-lineal del segmento. Así, por lo tanto, es aconsejable realizar representaciones no normalizadas para evitar este problema e incluir las normalizadas para poder realizar comparaciones.

CONCLUSIONES

El principal objetivo de este artículo fue proporcionar a los lectores una metodología para el estudio del comportamiento motor basada en los principios de la TSD. La herramienta presentada, los retratos de fase, permitió reducir la multidimensionalidad que forma el comportamiento motor a un parámetro de control (el trazado de la gráfica) y así facilitar el análisis. Con el análisis cualitativo de los retratos de fase fuimos capaces de mostrar cuales eran los patrones generales de las habilidades analizadas (marcha y el molino en la barra), así como poder discernir las singularidades de las características poblacionales (niños con deficiencias y sin deficiencias) o individuales a lo largo del proceso de aprendizaje (no iniciados y expertos en la habilidad). También, facilitó la observación de las adaptaciones del comportamiento a distintos entornos (cinta rodante, suelo, cama elástica, velcro y goma) y siempre analizando el proceso en cada intento y no únicamente el resultado. No obstante, los retratos de fase no son representaciones completas del comportamiento motor y deberíamos complementarlos con: (1) el análisis en otros planos del movimiento; (2) el análisis de la coordinación de ese segmento o articulación con otras implicadas en el movimiento; (3) utilizar variables cuantitativas que faciliten la interpretación de los gráficos.

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TABLAS

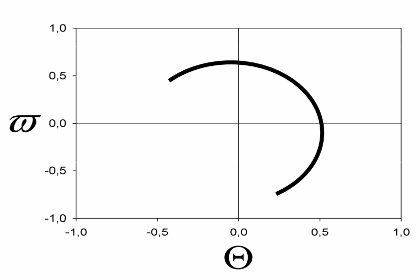
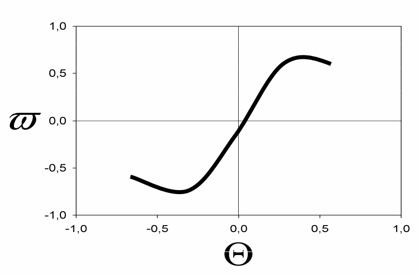
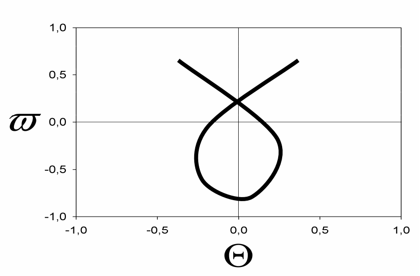
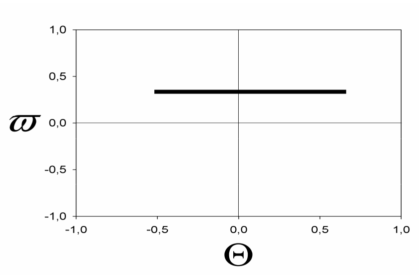
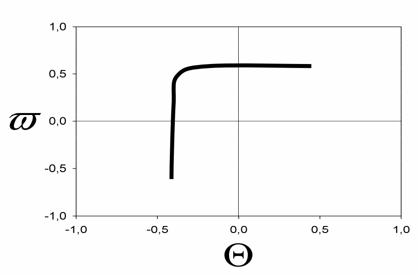
Representación gráfica	Interpretación
	La presencia de trayectorias suaves y redondeadas indica un patrón bien controlado y estable. Existen propiedades elásticas del sistema músculo-tendón involucradas en la producción de trayectorias suaves y redondeadas.
	Las inflexiones y protuberancias son mecanismos de control utilizados para parar y reiniciar el sistema.
	Los bucles (*“loops”*) que cruzan a velocidad 0 son considerados indicadores de la presencia de reversiones. Un gran número de cruces en el valor 0 podría sugerir un gran número de cambios en la dinámica del segmento.
	Una velocidad constante implica que la aceleración es 0 y por lo tanto la fuerza neta aplicada es 0. La presencia de velocidades constantes, observables en la presencia de mesetas, supone el aporte de un flujo continuo de energía para mantener el segmento en esa trayectoria restrictiva. En cambio, el movimiento libre bajo el influjo de las fuerzas pasivas, como la gravedad, se manifiesta a la inversa.
	La presencia de cantos cuadrados es una evidencia de acciones explosivas o balísticas. Los mecanismos de control actúan para parar o desacelerar la acción así como para acelerar el movimiento después de una trayectoria constante.

Tabla 1. Posibles formas que pueden asumir los retratos de fase y su interpretación.

TEXTOS DE LAS FIGURAS

Figura 1. A la izquierda, retratos de fase del muslo en la locomoción: a) niño portador del síndrome de Down corriendo en un suelo; c) adolescente portador de parálisis cerebral caminando en el suelo; e) niño portador del síndrome de Down caminando sobre una barra. Y a la derecha, retratos de fase del ángulo formado por el tronco y el muslo durante el balanceo en barra fija: b) gimnasta experto (categoría senior) realizando balanceos completos; d) niño gimnasta (categoría alevín) realizando balanceos completos; f) niño gimnasta de categoría alevín realizando balanceos no completos.

Figura 2. A la izquierda, retratos de fase del muslo de un bebé portador del síndrome de Down en un estadio pre-locomotor caminando en una cinta rodante: a) evaluación inicial; c) después de 3 meses de práctica en la cinta rodante; e) después de 5 meses de práctica en la cinta rodante. Y a la derecha, retratos de fase del segmento tronco en relación a los muslos en varias etapas de formación de los gimnastas en barra fija: b) balanceo de un niño gimnasta (categoría alevín) con 2 años de práctica; d) balanceo completo de un niño gimnasta (categoría alevín) con 4 años de práctica; e) balanceo completo de un adolescente gimnasta (categoría infantil) con 6 años de práctica.

Figura 3. Retrato de fase: a) de la pierna de un individuo de edad avanzada caminando con cadencia impuesta de 60 pasos/minuto por un suelo; b) de la cadera de un gimnasta experto realizando molinos a baja velocidad; c) de la pierna de un bebé portador del síndrome de Down caminando sobre una cinta rodante con protuberancias de goma (efecto distorsionado debido a la normalización); d) de la cadera de un niño gimnasta realizando balanceos en barra con poca amplitud de movimiento (efecto distorsionado debido a la normalización); e) de la pierna de un niño portador de síndrome de Down corriendo en el suelo; f) de la cadera de un niño gimnasta realizando un molino sin aprovechar las fuerzas externas; g) de la pierna de de un niño portador del síndrome de Down caminando en una cama elástica; h) de la cadera de un niño gimnasta realizando un molino aprovechando las fuerzas externas.

Figura 4. A la izquierda retrato de fase del muslo de los bebés portadores del síndrome de Down, en un estadio pre-locomotor, caminando en una cinta rodante: a) sin restricciones; c) superficie de velcro; e) y g) superficie con protuberancias de goma. A la derecha retratos de fase del ángulo muslo-tronco de jóvenes adultos en proceso de aprendizaje del balanceo en barra.

Figura 1

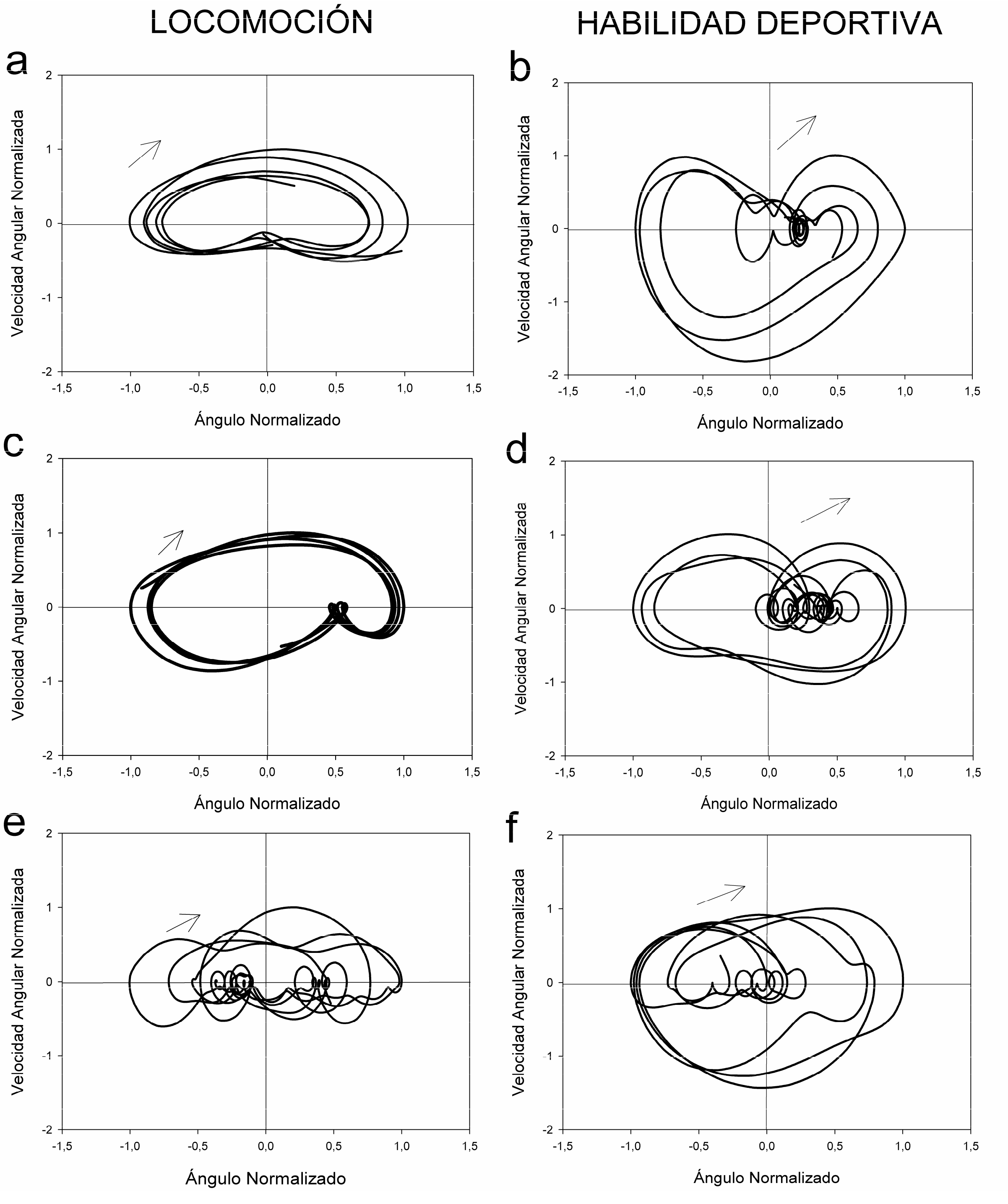
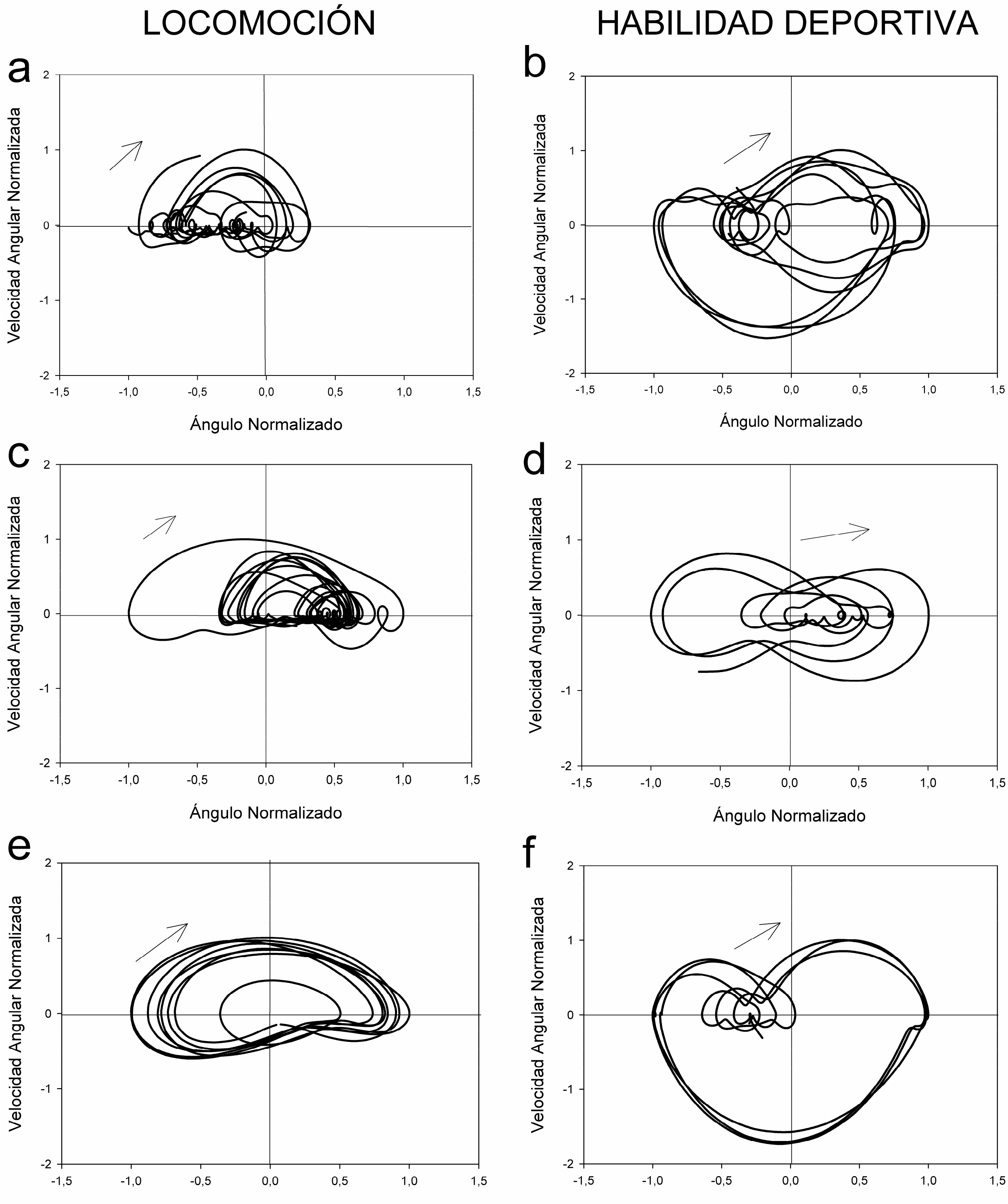

LOCOMOCIÓN
HABILIDAD DEPORTIVA
a
b
c
d
e
f
Velocidad Angular Normalizada
Ángulo Normalizado
2
1
0
-1
-2
-1,5
-1,0
-0,5
0,0
0,5
1,0
1,5

Figura 2


LOCOMOCIÓN
HABILIDAD DEPORTIVA
a
b
c
d
e
f
Velocidad Angular Normalizada
Ángulo Normalizado
2
1
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-2
-1,5
-1,0
-0,5
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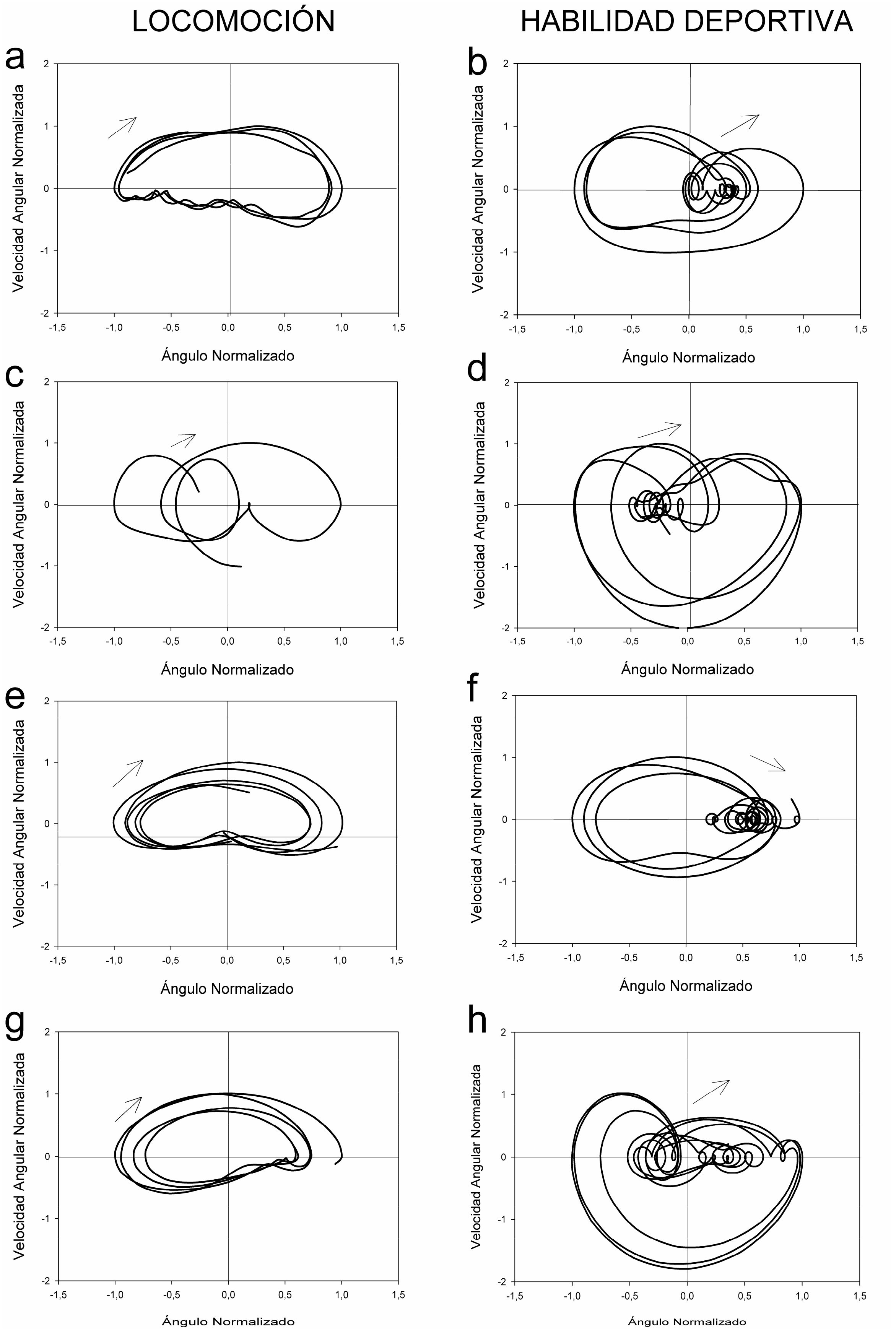
0,5
1,0
1,5

Figura 3


LOCOMOCIÓN
HABILIDAD DEPORTIVA
a
b
c
d
e
f
g
h
Velocidad Angular Normalizada
Ángulo Normalizado
2
1
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-1,5
-1,0
-0,5
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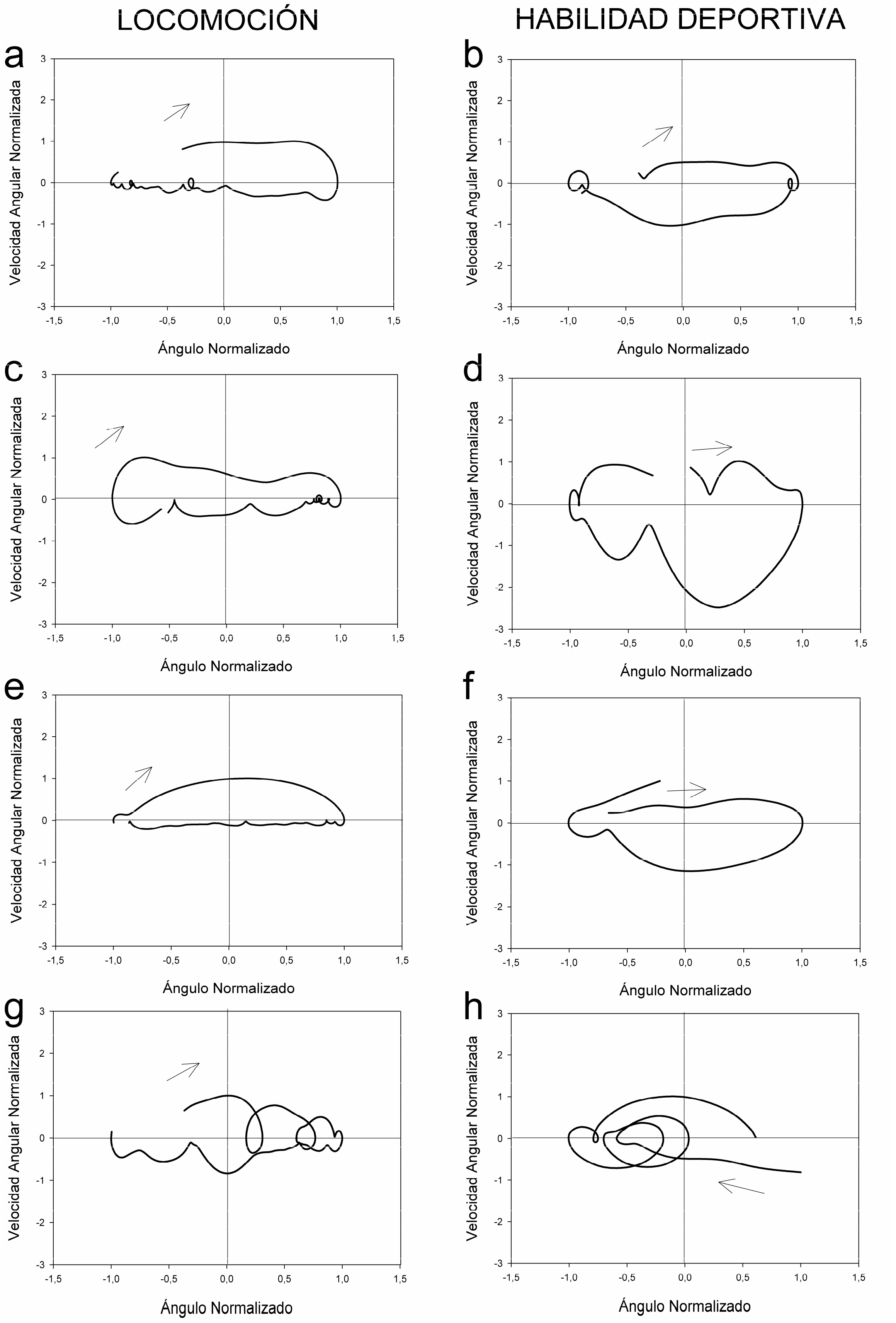
Figura 4


LOCOMOCIÓN
HABILIDAD DEPORTIVA
a
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f
g
h
Velocidad Angular Normalizada
Ángulo Normalizado
3
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-1,5
-1,0
-0,5
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0,5
1,0
1,5

Chapter 3. El ángulo de fase y la fase relativa continua para la investigación de la coordinación motora (Phase angle and continuous relative phase in motor coordination research)

Apunts. Educación Física y Deporte (in press)

TÍTULO:
EL ÁNGULO DE FASE Y LA FASE RELATIVA CONTINUA PARA LA INVESTIGACIÓN DE LA COORDINACIÓN MOTORA.

TITLE:
PHASE ANGLE AND CONTINUOUS RELATIVE PHASE IN MOTOR COORDINATION RESEARCH

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EL ÁNGULO DE FASE Y LA FASE RELATIVA CONTINUA PARA LA INVESTIGACIÓN DE LA COORDINACIÓN MOTORA.

Resumen

Todo proceso hacia la adquisición de una habilidad motora implica un aprendizaje, un control y una coordinación. La coordinación motora es generalmente definida como las relaciones espacio-temporales que existen entre diferentes segmentos corporales. El objetivo de este artículo es dar a conocer dos herramientas metodológicas para el estudio de la coordinación motora llamadas (1) ángulos de fase y (2) fase relativa continua. Estas técnicas posibilitan conocer la relación desplazamiento/velocidad angular de uno o varios segmentos durante todo el movimiento. En este artículo hemos aplicado dichas técnicas para generan unos gráficos cuyas trayectorias nos indicaron cómo los diferentes segmentos se coordinaban (en fase o fuera de fase). Con ello, pudimos conocer las estrategias coordinativas a las que los individuos recurrían al realizar una tarea nueva. A pesar de los resultados obtenidos, los ángulos de fase y la fase relativa continua no representaron el movimiento en su totalidad y se fundamentan en un análisis cualitativo. Por lo tanto, recomendamos al investigador tener en cuenta: (1) complementar el análisis con variables cuantitativas que reflejen la dinámica de los diferentes segmentos; y (2) seleccionar la normalización en función de las variables a analizar.

PALABRAS CLAVE: Aprendizaje motor, Biomecánica, Grados de libertad, Coordinación inter-segmentaria, Coordinación intra-segmentaria

PHASE ANGLE AND CONTINUOUS RELATIVE PHASE IN MOTOR COORDINATION RESEARCH

Abstract

The acquisition of motor skill is a process that involves learning, control and coordination. Motor coordination is generally defined as the spatio-temporal relationship among different body segments. The aim of this article is to present two methodological tools to analyze motor coordination: (1) phase angle and (2) continuous relative phase. These techniques allow the description of angular displacement/velocity relationships along the entire movement. In this manuscript we used these techniques to generate graphs that indicate segmental coordination in- or out-phase by means of qualitative analysis of its trajectories. With these results we know what coordination strategies subjects utilize to complete a task. Despite these results phase angle and continuous relative phase do not represent the complete movement and are mainly focused on qualitative analysis. Therefore, we recommend to researchers to: (1) add quantitative variables that reflect segmental dynamics, and (2) select normalization of the graphs as a function of the variable at hand.

KEYWORDS: Motor learning, Biomechanics, Degrees of freedom, Interlimb coordination, Intralimb coordination.

INTRODUCCIÓN

Una de las mayores preocupaciones de los investigadores del aprendizaje de habilidades motoras es conocer el proceso o mecanismo por el cual los individuos adquieren y modifican sus movimientos para alcanzar el objetivo de la tarea con un alto grado de eficacia y eficiencia (Sparrow & Irizarry-Lopez, 1987). Cuando la producción de una tarea permite resolver un problema motriz alcanzando las máximas expectativas de éxito y con un mínimo de tiempo y energía, estamos hablando de habilidad (Riera, 2005). Todo proceso hacia el logro de una habilidad motora comporta un aprendizaje, un control y una coordinación motora.

Según la aproximación de la Teoría de los Sistemas Dinámicos (TSD), el comportamiento es una consecuencia de las relaciones entre los múltiples subsistemas del organismo, como el estatus neural, características biomecánicas, experiencia, nivel de alerta, o la precisión visual, entre otros (Thelen & Ulrich, 1991; Kugler, Kelso, y Turvey, 1982; Ulrich, Ulrich, y Collier, 1992). De hecho, la adquisición de una habilidad motora se entiende como un comportamiento que surge de la interrelación entre la práctica y un conjunto de condicionantes (“*constraints*” en la literatura inglesa), categorizados en condicionantes del organismo, del entorno y de la tarea (Clark, 1995; Clark, 2002; Handford, Davids, Bennett, & Button, 1997; Holt, 2005; Kugler, Kelso, & Turvey, 1980; Marin, Bardy, & Bootsma, 1999; Newell, 1986; Nourrit, Deschamps, Lauriot, Caillou, & Delignieres, 2000; Thelen & Smith, 1994). El impacto relativo de estas tres categorías de limitantes en el perfil de coordinación varía de acuerdo con las circunstancias específicas. No obstante, la práctica es considerada generalmente el factor más importante para una mejora permanente de la capacidad de ejecución de una habilidad motora (Guadagnoli & Lee, 2004; Nourrit et al., 2000). Tanto es así que el logro del más alto nivel de habilidad en la ejecución de una tarea (ejecución del experto) requiere años de práctica (Clark, 1995; Guadagnoli & Lee, 2004).

Además la TSD define los sistemas que conforman a los individuos como sistemas abiertos, es decir, que se ven afectados por su interrelación o por las características específicas de la situación. Estas características dinámicas permiten al sistema modificar su comportamiento en el tiempo, lo cual da al sistema la capacidad de continua auto-organización. De hecho, es la inestabilidad del sistema lo que permite explorar nuevas organizaciones y coordinaciones motoras (Kelso, Scholz, y Schöner, 1986).

El aprendizaje motor puede ser considerado como una modificación de la dinámica de los sistemas para alcanzar el objetivo de la tarea. Es ampliamente aceptada la distinción de dos estadios en el aprendizaje de tareas motoras: (1) cuando el objetivo del individuo tiene que elaborar un nuevo modelo de coordinación, y (2) cuando el objetivo del individuo es ajustar los parámetros de una coordinación previamente aprendida. (Clark, 1995; Delignieres et al., 1998; Newell, 1991; Temprado et al., 1997). En cualquiera de los dos estadios la transición de un tipo de coordinación a otro, es decir de un estado del sistema a otro, no es necesariamente progresiva, sino que los cambios pueden ser abruptos y no-lineales. Estos cambios en las formas coordinativas suceden cuando subsistemas críticos (los parámetros de control) progresan lo suficiente como para generar un estado crítico o punto de transición, provocando un cambio cualitativo (bifurcación) y permitiendo la emergencia de un nuevo patrón de coordinación (nueva organización).

Por otro lado, se ha definido la coordinación motora como las relaciones espacio-temporales que existen entre los diferentes segmentos corporales durante la realización de una tarea (Delignieres, Teulier y Nourrit, *in press*). Para resolver una nueva coordinación el individuo tiene que reorganizar el control de un gran número variables. Todas las variables de un sistema que precisan ser controladas independientemente para el desarrollo de una tarea son denominadas grados de libertad. Una habilidad motora de un sistema abierto y no rígido, como por ejemplo sentarse, puede tener diversos grados de libertad según sus condicionantes.

Así, un niño pequeño a los 6 meses de edad puede caer para sentarse y con eso no precisa un control diferencial de la postura o control tónico-muscular, los cuales son dependientes de la actividad neural. No obstante, una persona mayor con problemas de equilibrio puede necesitar ampliar sus grados de libertad reclutando actividades adicionales de los músculos, atención y monitorización del sistema visual, además de los sistemas sensoriales involucrados normalmente en la postura (Tang y Woollacott, 1996). En el caso de un sistema constituido por una cadena de péndulos (considerando únicamente los segmentos corporales, por ejemplo) los grados de libertad pueden ser cuantificados contando cuantos segmentos y ejes participan en las dimensiones posibles (Meriam, 1966).

Si consideramos el cuerpo como un conjunto de sistemas de péndulos, los individuos que se enfrentan a una *nueva* tarea presentan dos soluciones generales para controlar la gran cantidad de grados de libertad: (1) congelar o fijar algunos grados de libertad (*"freezing degrees of freedom"* en la literatura inglesa), disminuyendo la movilidad de las articulaciones; y (2) realizar las acciones articulares simultáneamente (*"coupling degrees of freedom"* en la literatura inglesa), disminuyendo las diferencias temporales entre las acciones de los segmentos (Vereijken, van Emmerik, Whiting y Newell, 1992). La mejora en la habilidad motora es caracterizada por lo tanto en una disminución del control "congelado" o "acoplado" de los grados de libertad. Ello conlleva una "liberación" de dichos grados de libertad (*"freeing degrees of freedom"* en la literatura inglesa), y por la incorporación en un sistema dinámico controlado.

La complejidad de las operaciones entre los grados de libertad que actúan en la coordinación motora de una tarea, junto con la no-linealidad de los cambios a lo largo del proceso de aprendizaje, precisa de una aproximación científica capaz de deshacer este fenómeno multidimensional (Jensen, 2005). Los principios y herramientas de la TSD pueden ayudar a entender los orígenes, las formas de los comportamientos y las razones porqué estos patrones cambian (Clark y Phillips, 1991; Mauerberg, Schuller, y Fantucci, 1994; Mauerberg-deCastro y Angulo-Kinzler, 2000; Winstein y Garfinkel, 1989). El principal objetivo de este artículo es mostrar a los lectores dos herramientas metodológicas para el estudio de la coordinación del movimiento llamadas (1) ángulos de fase y (2) fase relativa continua. Estas técnicas permitirán al investigador el análisis de la relación espacio-temporal que existe entre dos segmentos y/o articulaciones durante un movimiento. La aplicación de esta metodología en distintos instantes permitirá la evaluación de los cambios de coordinación motora durante el aprendizaje. Para ejemplificar su aplicabilidad e identificar sus ventajas y limitaciones se aplican dichas técnicas a varias habilidades motrices analizadas en nuestros laboratorios (la locomoción y el balanceo en la barra fija).

EL ÁNGULO DE FASE (“*PHASE ANGLE*”) APLICADO AL ANÁLISIS DE LA COORDINACIÓN MOTORA

Para el estudio de la coordinación es necesaria una captación precisa de los datos que provienen de la actividad. Una de las mejores herramientas para el estudio de la coordinación del movimiento es la biomecánica, no sólo para describir los cambios que suceden, sino también para entender porque los cambios pasan (Winter y Eng, 1995; Ulrich y Kubo, 2005; "Knoek" van Soest y Ledebt, 2005; Jensen y Korff, 2005; Jensen, 2005; Holt, 2005). El análisis de la coordinación durante el proceso de aprendizaje precisa que los datos biomecánicos sean combinados con técnicas de reducción de datos (como por ejemplo el ángulo de fase o el ángulo relativo de fase) de forma que la representen y la expliquen.

Elaboración de los ángulos de fase

El análisis del movimiento puede ser simplificado utilizando medidas de un sistema de coordenadas en movimiento. Esta aproximación es conocida como análisis del movimiento relativo. Por el contrario, cuando el movimiento es especificado en base a un sistema de coordenadas fijas hablamos de movimiento absoluto. En el análisis del movimiento relativo, el movimiento del sistema de coordenadas puede ser de traslación, de rotación o una combinación de los dos. En consecuencia, se puede decir que en general existen sistemas de referencia traslacionales y sistemas de referencia rotacionales. Para el análisis de la coordinación de los diferentes segmentos corporales se consideran los sistemas de referencia rotacionales, ya que los segmentos se mueven a partir del eje articular. En la representación de los sistemas rotacionales se utilizan las coordenadas polares. En las coordenadas polares los ángulos de fase pueden ser derivados y graficados en series de tiempo, lo que nos ayudará a representar el movimiento de los diferentes segmentos y observar su coordinación.

El ángulo de fase es representado en el eje *y* mientras que el eje *x* muestra la duración del movimiento, habitualmente la duración está expresada en valores normalizados o en porcentajes. Los valores de los ángulos de fase son derivados de un retrato de fase (desplazamiento angular y velocidad angular de un segmento o articulación) graficados en un sistema de coordenadas polares. Cada una de las coordenadas “desplazamiento angular-velocidad angular” nos da un valor angular en relación a un cero establecido por convención (lado izquierdo del eje x en nuestro caso). Convencionalmente la dirección de las agujas del reloj ha sido elegida para computar los datos de la gráfica desplazamiento angular-velocidad angular.

A continuación se presentan las ecuaciones utilizadas para el cómputo de un gráfico de ángulo de fase (Clark & Phillips, 1993; Kelso, Saltzman, y Tuller, 1986; Kurz y Stergiou, 2002; Kurz y Stergiou, 2004; Mauerberg-deCastro y Angulo-Kinzler, 2001 Wheat y Glazier, 2006)

1. Primero, el desplazamiento angular es normalizado.

$$\Theta \mathrm{i} = \left(\frac{2 \times [\Theta \mathrm{i} - \min(\Theta \mathrm{i})]}{\max(\Theta \mathrm{i}) - \min(\Theta \mathrm{i})} \right) - 1$$

Donde Θ (grados) son los ángulos del recorrido articular

2. A continuación, la velocidad angular es normalizada en función a su máximo. La velocidad angular igual a cero ha de corresponder a una velocidad angular normalizada igual a cero.

$$\omega i = \frac{\omega i}{\max(\omega \mathrm{i})}$$

Donde ω (grados/segundos) son la velocidad angular del recorrido articular

3. El ángulo articular recorrido y la velocidad angular normalizados permiten el cálculo del ángulo de fase (AF).

$$AF = \arctan\left(\frac{\omega i}{\Theta \mathrm{i}} \right)$$

Donde Θ (grados) son los ángulos del recorrido articular y ω (grados/segundos) son la velocidad angular del recorrido articular

4. El ángulo de fase ha de ser corregido en función del cuadrante a que pertenece en el retrato de fase (Tabla 1). Sin la corrección el trazado de la gráfica del ángulo de fase perdería su continuidad y mostraría valores iguales para puntos con el mismo valor absoluto pero de diferente signo (positivo o negativo). En la Figura 1 se presenta un ejemplo realizado a partir de datos no reales con el fin de facilitar la comprensión de la realización e interpretación de los ángulos de fase. En este caso, sin la corrección todos los puntos señalados en la Figura 1a (P1, P2, P3, P4, P5 y P6) obtendrían el mismo valor de ángulo de fase.

TABLA 1

Interpretación de los ángulos de fase

Los ángulos de fase se suelen interpretar de forma cualitativa. Para una sola variable el gráfico del ángulo de fase nos informa sobre la relación desplazamiento/velocidad angular de un segmento durante todo el movimiento. Generalmente los ángulos de fase se suelen graficar en relación al tiempo o el recorrido del movimiento expresados en porcentaje para facilitar posibles comparaciones. Si el trazado es lineal y evoluciona en un pico positivo, sabemos que el segmento está en movimiento con una relación de cambio constante entre desplazamiento y velocidad angular (como por ejemplo, el ángulo de fase entre P1-P2 en la Figura 1b). En cambio, si el trazado del ángulo de fase se vuelve plano como en el descrito entre los puntos P3-P4 o P5-P6 de la Figura 1b, quiere decir que el segmento no está cambiando su relación desplazamiento/velocidad angular (Fig. 1a). Cuando la trayectoria del gráfico del ángulo de fase se vuelve no-lineal, es decir, cambia de una dirección positiva hacia una negativa o viceversa, significa que el segmento está cambiando su dirección de rotación (reversión), por ejemplo pasa de una extensión a una flexión (en el 50% del ciclo de la Figura 1b).

FIGURA 1

La representación simultánea de los ángulos de fase de dos segmentos permite ver la coordinación del sistema. Dicha coordinación se denomina intra-segmentaria si los dos segmentos pertenecen a la misma extremidad (rodilla y tobillo, por ejemplo), o inter-segmentaria si los dos segmentos pertenecen a extremidades distintas (rodilla derecha y rodilla izquierda). Si las trayectorias de los gráficos corren paralelos, los dos segmentos están acoplados “en fase”. Al contrario, si un trazado va en la dirección opuesta al otro o no hay cambio en uno de los dos trazados mientras el otro cambia, los segmentos están desacoplados o “fuera de fase”.

Para ilustrar el concepto de coordinación se representan dos ejemplos de acoplamiento en fase y dos fuera de fase en la Figura 2. Los gráficos de locomoción son presentados con el tiempo de cada ciclo en el eje de abscisas *x* (desde la retirada del pie del suelo hasta la siguiente retirada del pie) expresado en porcentaje de 0% a 100% (Fig 2a i 2c). En la Figura 2a un bebé portador del síndrome de Down exhibe dos porciones de la trayectoria donde hay una relación fuera de fase entre la pierna y el muslo (coordinación intra-segmentaria). La primera sucede en el inicio del ciclo y la segunda toma la mayor parte de la fase de apoyo, fase iniciada con el contacto del pie en el suelo (cps). En el momento del contacto del pie con el suelo la pierna se mantiene sin alteración (meseta en la trayectoria del gráfico) y el muslo, después de una pequeña inflexión, continúa en movimiento. Se observa una segunda inflexión por parte del muslo alrededor del 65% de duración del ciclo, lo que indica cierto grado de reversión. Por otro lado, la pierna se mantiene estable hasta la segunda inflexión del muslo y a partir del 65% del ciclo reinicia el movimiento. En cambio la Figura 2c muestra dos líneas paralelas y bien acopladas (en fase). Esto significa que el muslo y la pierna realizan simultáneamente el mismo movimiento a lo largo del ciclo. En este caso no existe acción de la rodilla que debería actuar como amortiguador, tal y como sucede en la Fig. 2a. Así, la rigidez de la articulación de la rodilla hace perder un grado de libertad al movimiento.

El segundo ejemplo pertenece a dos jóvenes adultos en proceso de adquisición de una nueva habilidad, balancearse en la barra fija (Fig. 2b y 2d). Los gráficos de la habilidad deportiva son presentados con el recorrido de cada ciclo (desde la máxima altura de la cadera por detrás de la barra hasta la máxima altura de la cadera por delante) expresado en porcentaje de -100% a 0% en el recorrido de bajada y del 0% al +100% en el recorrido de subida (Fig. 2b y 2d). De esta forma, la máxima altura posible por detrás de la barra (proyección vertical de la cadera encima de la barra) equivaldría al -100%; la mínima altura posible (proyección vertical de la cadera debajo de la barra) equivaldría al 0%; y la máxima altura posible por delante de la barra (proyección vertical de la cadera encima de la barra) equivaldría al 100%. En este ejemplo se representan el movimiento de la cadera y el hombro, por ello hablamos de coordinación inter-segmentaria. El primer sujeto (Fig. 2b) muestra una coordinación secuencial o fuera de fase entre las acciones del hombro y de la cadera del -20% al 0% y del 20% al 60% del ciclo. Mientras que el resto del movimiento se produce en paralelo ("*off-set*"), es decir, realizan el mismo movimiento pero con valor diferente de ángulo de fase. Durante el recorrido de la gráfica en porcentajes negativos del ciclo (fase de descenso del balanceo), el hombro realiza primero la acción y posteriormente la cadera. En cambio, en los porcentajes positivos del ciclo (fase de ascenso del balanceo), la cadera se avanza a la acción del hombro. Por otro lado, el participante representado en la Figura 2d muestra una coordinación simultanea o en fase desde el porcentaje de ciclo -20 hasta el 60.

FIGURA 2

Limitaciones de los ángulos de fase

La representación del ángulo de fase tiene la ventaja de mostrar el grado de acoplamiento entre dos segmentos. Sin embargo, dos comportamientos motores distintos pueden producir el mismo ángulo de fase. Por ejemplo, un desplazamiento de 20 grados a una velocidad angular de 20 grados/segundo será representado por un ángulo de fase igual a un desplazamiento de 1 grado a una velocidad de 1 grado/segundo, ya que dicha representación se calcula a partir de la tangente de estos valores como coordenadas. Para evitar este problema podríamos añadir el valor del radio de cada punto en la trayectoria a lo largo de las coordenadas polares.

Por razones similares algunos autores (Kurz et al., 2002; Kurz et al., 2004) apuntan que el cálculo del ángulo de fase a partir de valores normalizados en el retrato de fase (desplazamiento angular versus velocidad angular) puede exagerar las modificaciones producidas por dicha normalización. Según los mismos autores, el cálculo de los ángulos de fase y de la fase relativa (a continuación en este mismo artículo) no precisaría de una normalización previa ya que la amplitud de los movimientos de los segmentos no altera el resultado debido a las propiedades de la función arco tangente. No obstante, como veremos más adelante, la técnica de normalización exacta dependerá del interés de la pregunta de investigación y de las características de los datos (Peters, Haddad, Heiderscheit, Van Emmerik, y Hamill, 2003).

Además, el uso del ángulo de fase no permite establecer la contribución de la cinemática angular de los segmentos al movimiento, debido al uso simultáneo de desplazamiento y velocidad angular para su cálculo. Para ello es necesario el uso de otras técnicas que complementen el ángulo de fase, como por ejemplo la técnica de los retratos de fase que describen el desplazamiento/velocidad angular de cada segmento.

Finalmente, también hemos de tener en cuenta que la interpretación de los gráficos del ángulo de fase acaba por sufrir ambigüedades causadas por el subjetivismo del investigador al hacer el análisis cualitativo. Para dar mayor consistencia a la interpretación se suele complementar los estudios con el análisis de variables cuantitativas extraídas del mismo ángulo de fase. Es decir, se eligen momentos importantes en la tarea y se comparan valores del ángulo de fase en esos momentos en varios sujetos o bien antes y después de un proceso de aprendizaje.

LA FASE RELATIVA CONTINUA (“*CONTINUOUS RELATIVE PHASE*”) APLICADA AL ANÁLISIS DE LA COORDINACIÓN MOTORA

Elaboración de la fase relativa continua

Otra técnica de reducción de datos utilizada para el análisis de la coordinación es la fase relativa continua. La fase relativa se basa en la relación temporal de dos sistemas, es decir, la relación de fase entre dos segmentos corporal, o entre dos segmentos corporales y un evento específico. La fase relativa continua puede ser derivada de diferentes herramientas de reducción de datos. Algunos investigadores utilizan el desplazamiento vertical, horizontal o resultante (vertical/horizontal) y otros la derivan de los ángulos de fase. Si se deriva la fase relativa de los ángulos de fase, el cálculo es el siguiente (Clark et al., 1993; Kurz et al., 2002; Kurz et al., 2004; Wheat et al., 2006):

1. Los ángulos de fase de los segmentos (calculados siguiendo la metodología anteriormente explicada) permiten el cálculo de la fase relativa.
2. La fase relativa (Φ) se define como la diferencia entre el ángulo de fase del segmento distal con el ángulo de fase del segmento proximal en cada instante.

$$\Phi = AF\text{d} - AF\text{p}$$

Donde AF_{d} es el ángulo de fase del segmento distal y AF_{p} es el ángulo de fase del segmento proximal.

Interpretación de la fase relativa continua

Los valores de la fase relativa continua permiten determinar el tipo de coordinación. Definimos una coordinación en fase (0º) si los dos segmentos o articulaciones se mueven sincrónicamente. Por el contrario, la coordinación es en anti-fase (±180º) si los segmentos o articulaciones se mueven en direcciones opuestas. Además, podemos encontrar múltiples modos de coordinación intermedios, llamados fuera de fase, entre las coordinaciones en fase o anti-fase. Por otro lado, el signo (positivo o negativo) de los valores de la fase relativa continua expresan que segmento antecede al otro en la coordinación del movimiento. Si los valores son positivos el segmento distal realiza el movimiento antes que el proximal y si los valores son negativos el segmento proximal precede al distal.

Las gráficas incluidas en la Figura 3 son ejemplos de fase relativa continua derivados de los ángulos de fase de las gráficas presentadas en la Figura 2. La diferencia entre los ángulos de fase, del muslo y de la pierna en el caso de la locomoción y de la cadera y del hombro para el balanceo en al barra, indican que los dos segmentos se están moviendo en fase cuando la línea se desplaza a lo largo del eje cero (Fig. 3c y 3d). Sin embargo, pendientes en la dirección negativa o positiva indican que el sistema está fuera-de-fase (Fig. 3a y 3b) e incluso se llega a valores de anti-fase al alcanzar el 60% del ciclo de marcha (Fig. 3a). En la Figura 3b podemos observar que entre el -60% y el -20% del ciclo del balanceo la cadera antecede al hombro y entre el 40% y el 60% el hombro precede el movimiento.

FIGURA 3

La fase relativa continua, como técnica que permite resumir la coordinación motora, tiene un gran potencial para ser un buen descriptor de la esencia del movimiento que realiza el sistema (individuo). Su variabilidad refleja la estabilidad del sistema como un todo. El aprendizaje motor implica que el individuo modifica la coordinación de los segmentos implicados para adecuarse al objetivo de la tarea y realizarla de forma más eficaz y eficiente. Por lo tanto, los cambios entre intentos en los valores de la fase relativa continua nos muestran diferentes coordinaciones y son un indicador de la reorganización del sistema que normalmente ocurre en el proceso de aprendizaje. En la Figura 4 se observa la fase relativa continua obtenida por parte de un mismo individuo en la ejecución de un balanceo en la barra fija el primer día de práctica (Fig. 4a) y después de realizar 18 sesiones de práctica (Fig. 4b). El primer día de práctica la fase relativa continua muestra una coordinación en fase, próxima a 0º, la mayor parte del ciclo (Fig. 4a). En cambio, después del periodo de práctica el movimiento se inicia con una coordinación fuera de fase con un movimiento de hombro que precede al de cadera, progresivamente la cadera va adelantando al hombro hasta llegar a antecederlo en el 0% del ciclo y a partir de este punto el hombro progresivamente vuelve a preceder a la cadera (Fig. 4b).

FIGURA 4

Así, esta técnica puede apuntar bifurcaciones o cambios en la coordinación del movimiento. Si un sistema muestra un cambio en la fase relativa continua, por ejemplo como sucede en la Figura 4 pasando de una forma predominantemente en fase a una fundamentalmente fuera de fase, decimos que el sistema pasa por una bifurcación. Esta identificación es importante para plantear intervenciones en el aprendizaje ya que las intervenciones tienen más garantía de inducir cambio si (1) se focalizan en buscar la bifurcación en la fase relativa continua de los segmentos adecuados, y (2) se implantan en una etapa en la que el sistema ya tiende hacia el cambio.

Limitaciones de la fase relativa continua

La fase relativa continua, como cualquier otra herramienta de análisis, presenta algunas carencias. Una de las limitaciones más importantes es que como mínimo uno de los componentes del sistema analizado ha de demostrar un comportamiento cíclico o repetitivo. Es muy difícil computar e interpretar la fase relativa entre dos segmentos corporales que son movidos una sola vez (comportamiento acíclico).

Además, las técnicas de normalización usadas en el cálculo de la fase relativa continua asumen que estamos analizando una señal oscilatoria (similares a un péndulo) y, por lo tanto, puede no ser apropiado para osciladores parciales o de trayectorias no-sinusoidales (Peters et al., 2003). Además, como hemos comentado anteriormente, la técnica de normalización exacta dependerá del interés de la pregunta de investigación. Si los datos son sinusoidales, la técnica específica de normalización es irrelevante porqué cualquiera técnica utilizada escalaría la velocidad de forma que el resultado final sería un gráfico desplazamiento angular-velocidad angular de forma circular. Cuando los datos son no-sinusoidales, varias técnicas de normalización pueden ser utilizadas, siempre con el objetivo de hacer el retrato de fase más circular. Los datos no sinusoidales utilizan entre otras técnicas de normalización la reescala del eje vertical de coordenadas, otras técnicas más sofisticadas de transformación o metodologías no-lineales (Peters et al., 2003).

Por otra parte, el investigador debe tener en cuenta que al calcular las relaciones de fase, las formas del retrato de fase son ignoradas y solo nos centramos en el sincronismo del movimiento de los segmentos corporales. Cuando las formas del retrato de fase son ignoradas, no es posible deducir que estrategias de control están involucradas. Al igual que sucedía con la técnica de ángulos de fase, la técnica de fase relativa continua debe ser complementada con el uso de otras técnicas que describan el comportamiento cualitativo de los segmentos, como por ejemplo los mismos retratos de fase.

CONCLUSIONES

El principal objetivo de este artículo fue mostrar a los lectores una metodología para el estudio de la coordinación del movimiento. Tanto los ángulos de fase como la fase relativa continua permitieron analizar la coordinación del movimiento a partir de una variable (el trazado de su representación gráfica). A través del análisis cualitativo de ambas técnicas fuimos capaces de diferenciar que partes del movimiento se realizan en fase o fuera de fase. También pudimos explicar que estrategia de coordinación ("congelar" o "acoplar" los ángulos de libertad) utilizaban los individuos analizados al realizar una nueva tarea. No obstante, ni los ángulos de fase ni la fase relativa continua son representaciones completas de la coordinación. El análisis debería ser complementado con herramientas que reflejen la dinámica de los diferentes segmentos, como los retratos de fase. Otra limitación a tener en cuenta es la normalización a realizar y las interpretaciones que se derivan de cada tipo de normalización.

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TABLAS

Θ_i	ω_i	Operación	Fórmula aplicada
+	+	convertir a grados	$=57.3\times\left(a\tan\left(\frac{\omega i}{\Theta i}\right)\right)$
-	+	180 + (grados obtenidos)	$=180+\left(57.3\times\left(a\tan\left(\frac{\omega i}{\Theta i}\right)\right)\right)$
-	-	180 – (grados obtenidos)	$=180-\left(57.3\times\left(a\tan\left(\frac{\omega i}{\Theta i}\right)\right)\right)$
+	-	valor absoluto de los grados obtenidos	$=57.3\times\left\lvert\left(a\tan\left(\frac{\omega i}{\Theta i}\right)\right)\right\rvert$

Tabla 1. Corrección de la señal en función del cuadrante a que pertenece en el retrato de fase (Hamill, van Emmerik, Heiderscheit, y Li, 1999).

TEXTO DE LAS FIGURAS

Figura 1. Retrato de fase realizado a partir de datos no reales en el cual se muestra la obtención de los ángulos de fase corregidos (α_{P1}, α_{P2} y α_{P3}) en diferentes puntos (Fig.1a, en la izquierda). El ángulo de fase obtenido a partir de los mismos datos no reales (Fig. 1b, en la derecha).

Figura 2. A la izquierda, ángulos de fase de la marcha sobre cinta rodante de dos ciclos mostrados por un bebé portador del síndrome de Down (rps= retirada del pie del suelo; cps= contacto del pie en el suelo). El tiempo transcurrido por cada ciclo (acción entre la primera retirada del pie y la segunda) está expresado en porcentaje de 0% a 100% en el eje de abscisas *x*. Y a la derecha, ángulos de fase del balanceo en barra mostrados por dos jóvenes adultos en proceso de aprendizaje. El espacio recorrido en cada ciclo (acción entre la máxima altura de la cadera por detrás de la barra y la máxima altura de la cadera por delante) está expresado en porcentaje de -100% a 0% en el movimiento de bajada del balanceo y 0% a +100% en el movimiento de subida.

Figura 3. Fase relativa continua del ángulo de fase de la marcha sobre cinta rodante de los dos ciclos mostrados en las Figura 2a y 2c de un bebé portador del síndrome de Down (a y c), y del balanceo en barra mostrados en las Figuras 2b y 2d de dos jóvenes adultos en el periodo de aprendizaje (b y d).

Figura 4. Fase relativa continua entre el hombro y la cadera de un individuo realizando un balanceo en barra fija antes de un periodo de práctica (Fig. 4a) y del mismo individuo después de 18 sesiones de práctica (Fig. 4b).

Figure 1

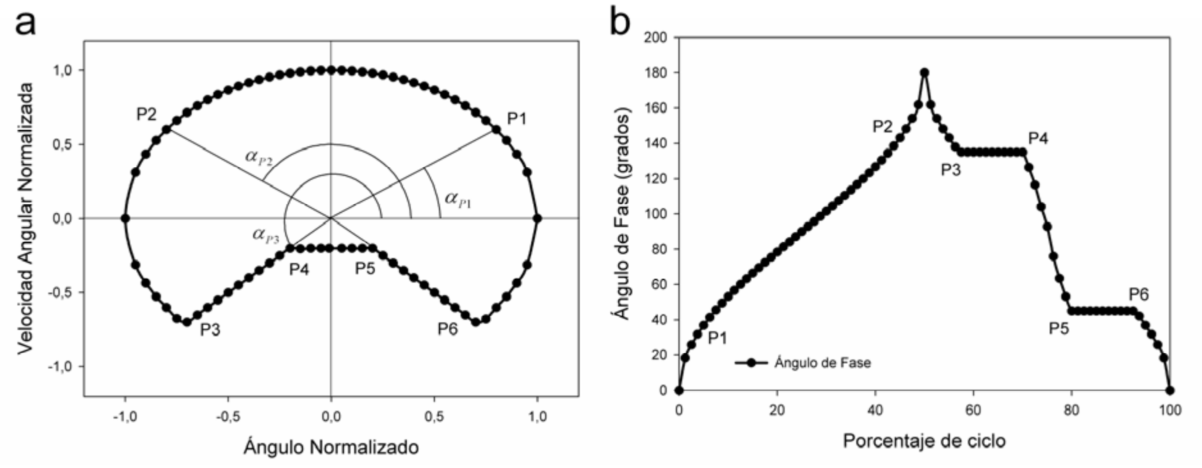
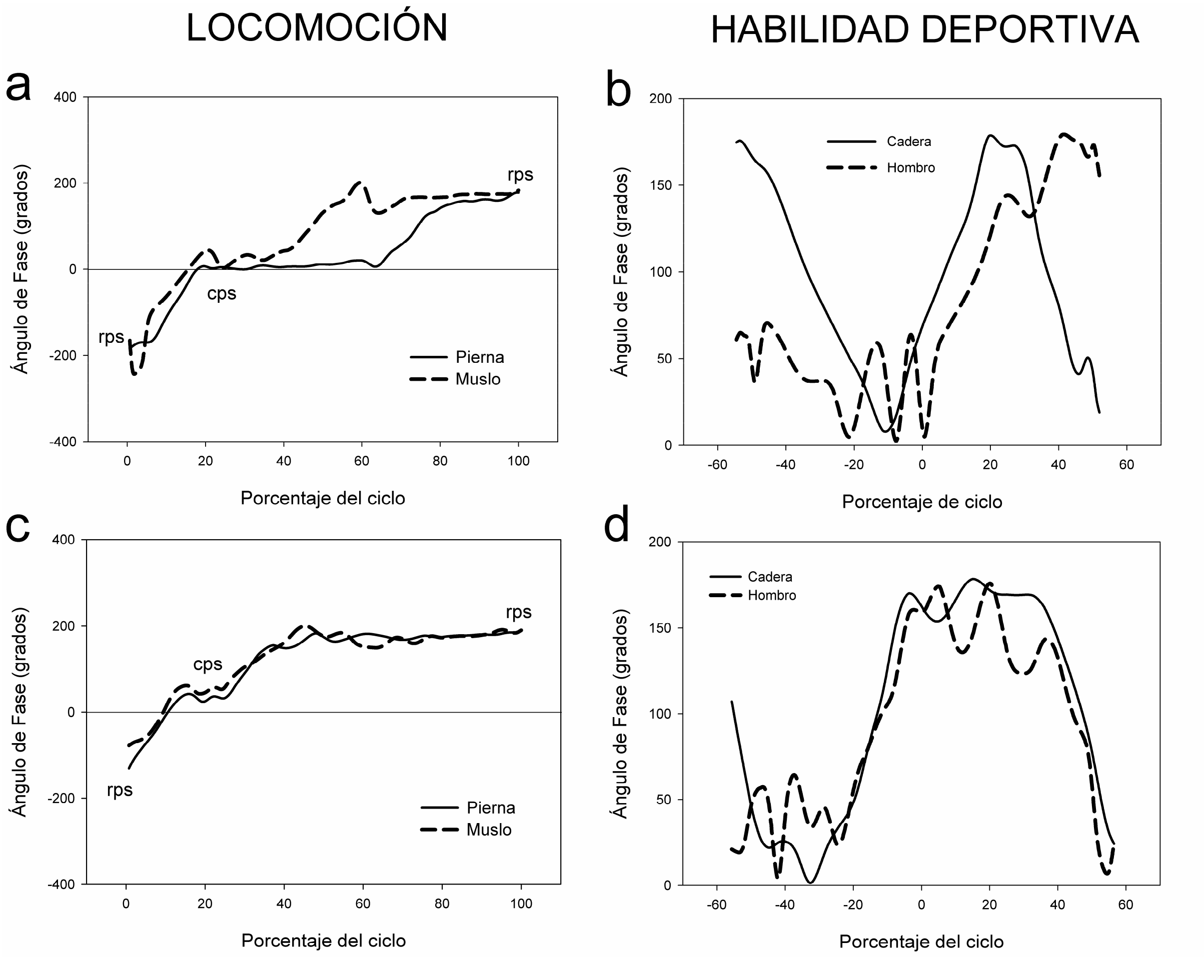

a
Velocidad Angular Normalizada
1,0
0,5
0,0
-0,5
-1,0
-1,0
-0,5
0,0
0,5
1,0
Ángulo Normalizado
P1
P2
P3
P4
P5
P6
α_{P1}
α_{P2}
α_{P3}
b
Ángulo de Fase (grados)
200
180
160
140
120
100
80
60
40
20
0
0
20
40
60
80
100
Porcentaje de ciclo
Ángulo de Fase
P1
P2
P3
P4
P5
P6

Figure 2


LOCOMOCIÓN
HABILIDAD DEPORTIVA
a
Ángulo de Fase (grados)
400
200
0
-200
-400
rps
cps
rps
Pierna
Muslo
0
20
40
60
80
100
Porcentaje del ciclo
b
Ángulo de Fase (grados)
200
150
100
50
0
Cadera
Hombro
-60
-40
-20
0
20
40
60
Porcentaje de ciclo
c
Ángulo de Fase (grados)
400
200
0
-200
-400
cps
rps
rps
Pierna
Muslo
0
20
40
60
80
100
Porcentaje del ciclo
d
Ángulo de Fase (grados)
200
150
100
50
0
Cadera
Hombro
-60
-40
-20
0
20
40
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Porcentaje del ciclo

Figure 3

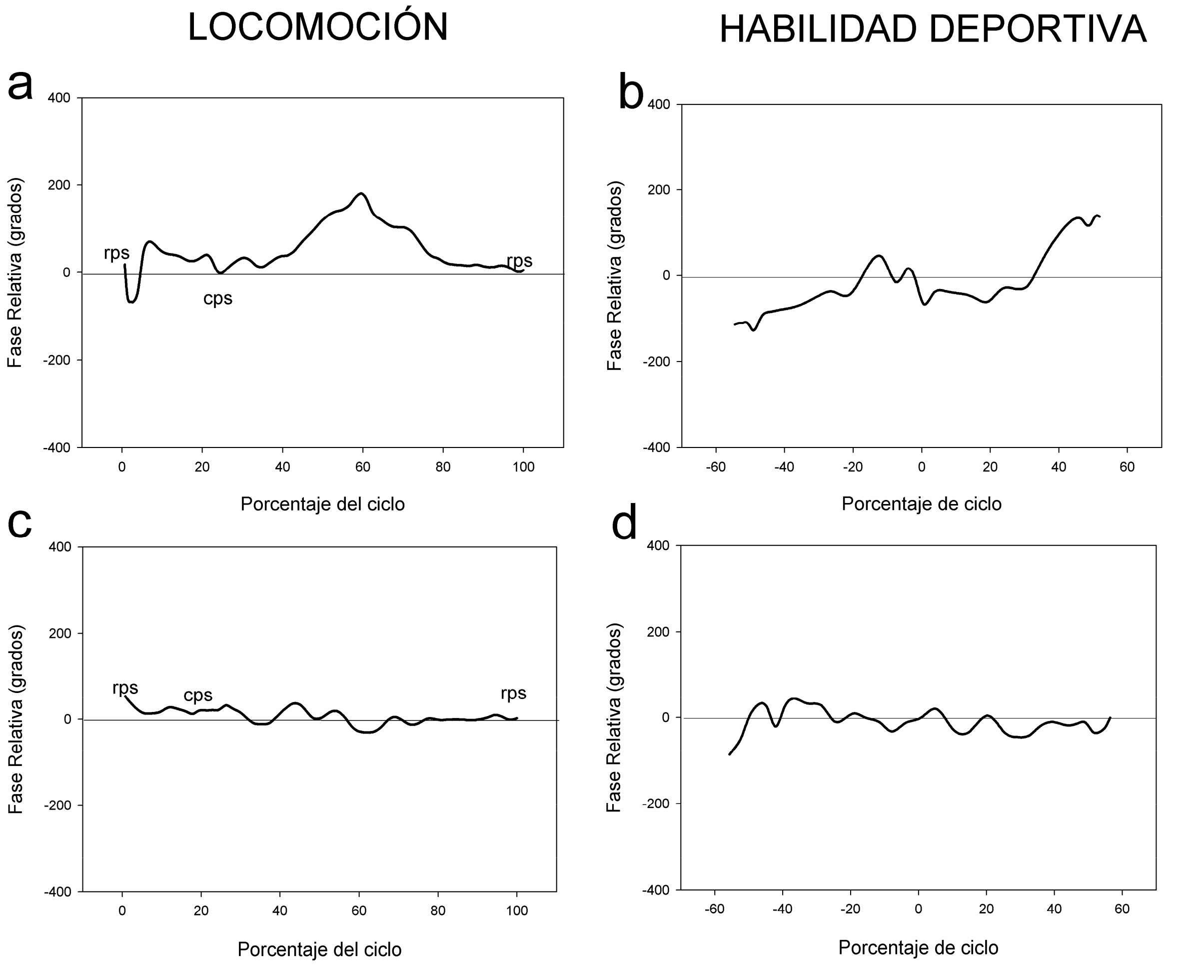
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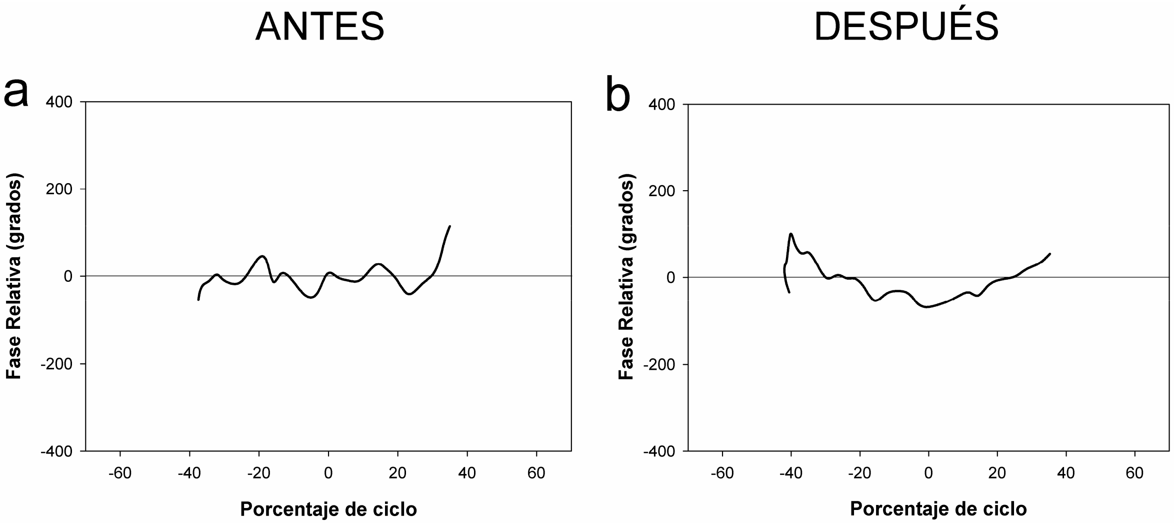
Figure 4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Porcentaje de ciclo

Chapter 4. Swing high bar performance in novice adults: Effects of practice and talent

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Swing high bar performance in novice adults: Effects of practice and talent

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Swing high bar performance in novice adults: Effects of practice and talent

Abstract

An individual’s a-priori talent could impact movement performance during learning. Also, task requirements and motor-perceptual factors are critical to the learning process. This study describes changes in the high bar swing performance after a two-month practice period. 25 novice participants who were divided by a-priory talent level (spontaneous-talented, ST, and non-spontaneous-talented, NST), and compared to experienced gymnasts. Additionally, their performance level perception before and after practice was assessed. We defined three events independently for hip (H) and shoulder (S) angle joints, and the lag between consecutive events (phases): the smallest angle during downswing (P1H, P1S); the largest angle after P1 (P2H, P2S); and the smaller angle during upswing (P3H, P3S). Movement performance variables were the maximum elevation on the downswing (Pi) and on the upswing (Pf), and the total path between both (swing amplitude). Data were collected during pre- and post-practice sessions by two video cameras. At the end of both sessions participants drew a sketch to represent their perception of their own level of performance relative to the Pi, Pf and the hip events. Results showed a similar practice effect in the swing amplitude in both novice groups. However, the ST group’s performance and perception variables on the downswing improved more than those of the NST group due to practice. This study suggests that: (1) improvements in the downswing were easier than in the upswing possibly due to familiarity of the visual reference in combination with proprioceptive feedback, and (2) being ST may involve a better or faster gain in perception of self-action compared to NST.

Key words: Motor-perceptual learning; Novel task; Initial conditions; Practice effect; Gymnasts

Swing high bar performance in novice adults: Effects of practice and talent

A major concern of motor skill learning theorists is the processes or mechanisms by which individuals refine their movements so that the goal of the activity is eventually achieved with a degree of precision and consistency (Sparrow & Irizarry-Lopez, 1987). It is widely accepted to distinguish two stages in the learning of motor-perceptual tasks: (1) when the person has to elaborate a novel mode of coordination, and (2) when the goal of the individual is to adjust the parameters of a previously learned coordination (Clark, 1995; Delignieres et al., 1998; Newell, 1991). Similarly, the acquisition of a motor skill is conceived as an emergent property from the interplay between practice and a set of interrelated constraints (Kugler, Kelso, & Turvey, 1980; Nourrit, Deschamps, Lauriot, Caillou, & Delignieres, 2000). These constraints have been categorized as environmental, task and organismic (Clark, 1995; Newell, 1986; Nourrit et al., 2000). The relative impact of these three categories of constraints on the pattern of coordination varies according to the specific circumstances. However, practice is generally considered to be the single most important factor responsible for the permanent improvement in the ability to perform a motor skill (Guadagnoli & Lee, 2004; Nourrit et al., 2000).

Changes in movement performance, that is learning, will be highly impacted not only by the amount and quality of practice individuals may accumulate but by their a-priori or spontaneous talent (Davids, Lees, & Burwitz, 2000; Elferink-Gemser, Visscher, Lemmink, & Mulder, 2007), For the purpose of this study spontaneous talent was defined as the individual's initial capacity to successfully perform a skill due to some developmental potential. In fact, the analysis of the initial state of the system constitutes a key point for understanding motor learning. Motor learning does not succeed 'de novo', but rather against the backdrop of pre-existing capacities (Delignieres et al., 1998). Teulier & Delignières' study (2007) found that participants do not possess the same skill level at the beginning of practice and changes in performance via further practice differed among them. They suggested that these differences could arise from individual-specific organismic constraints.

Focusing on motor-perceptual factors, motor learning is conceived also as the search for the optimal solution in the motor-perceptual workspace (Nourrit et al., 2000). Motor learning has been closely associated with the ability to correctly perceive the environment through peripheral sensory systems, as well as to centrally process and integrate proprioceptive, visual, and vestibular inputs at the level of the central nervous system (CNS) (Hatzitaki, Zisi, Kollias, & Kioumourtzoglou, 2002). Part of becoming skilled at a task involves learning to effectively use the sources of information available (Robertson & Elliott, 1996).

Learning sport skills represents an ideal situation to assess both, motor and perceptual changes. In fact, improvements in performance due to practice in gymnastics have been previously examined (Delignieres et al., 1998). We selected the longswing on the high bar in gymnastics as the focus of this study. The majority of movements on the high bar belong to a group of rotations in the vertical plane around a horizontal axis (Brüggemann, Cheetham, Alp, & Arampatzis, 1994). The coaching literature identified the ‘regular’ or ‘traditional’ backward longswing on high bar as a key basic skill, because of its association with the development of more complex high bar movements (Hiley & Yeadon, 2003; Irwin & Kerwin, 2005; Irwin & Kerwin, 2007b). The aim of the ‘regular’ backward swing is to go from handstand to handstand position through rotation around high bar with a straight body (Hiley et al., 2003). The quality of this movement is defined by the Fédération Internationale de Gymnastique (FIG) Code of Points (2009) where arms and legs full extension during the whole movement is expected. Several studies documented the key elements of ‘good’ high bar swing mechanics, emphasizing the importance of the hip and shoulder flexion and extension for the successful execution of the swing (Arampatzis & Bruggemann, 1999; Hiley et al., 2003; Yeadon & Hiley, 2000). Mechanically, the most important functional characteristics of the swing have been identified as a rapid hyper-extension to flexion of the hip after the gymnast passes through the lowest part of the circle (Brüggemann et al., 1994; Hiley et al., 2003; Irwin & Kerwin, 2007a; Irwin et al., 2007b; Yeadon et al., 2000) and flexion to extension of the shoulder joint before the highest point of the circle (Hiley et al., 2003; Irwin et al., 2007a; Irwin et al., 2007b; Yeadon et al., 2000). Irwin and Kerwin (2005, 2007) termed these phases of the hips and shoulders as the 'functional phases'. Yeadon and Hiley (2000) explained the gymnast's movement profile as an attempt to create a positive balance between the angular momentum created during the downswing and the angular momentum lost in the ascending phase. In this way, the hip functional phase reduces the radius between the center of mass (CM) and the rotational axis to help in the maintenance of the angular momentum (Irwin et al., 2005; Irwin et al., 2007b; Yeadon et al., 2000), and the shoulder functional phase pushes up the CM over the bar to continue gaining potential energy.

In previous research, various aspects of the swing on high bar have been investigated, including optimal kinematics and kinetics to perform it (Arampatzis et al., 1999; Hiley et al., 2003; Yeadon et al., 2000), and comparison of swing progression exercises to optimal skill performance (Irwin et al., 2005; Irwin et al., 2007a; Irwin et al., 2007b). However, no studies have been designed to examine learning (performance gains) of the high bar swing considering the a-priori talent of the individual, the practice effects, and the perceptual learning factors involved in the acquisition of this skill.

The main purpose of this study was three-fold: (1) To describe movement performance changes after a two-month practice period of a novel task (swing on high bar) in novices, (2) To examine differential practice effects within the novice cohort considering initial level of performance, that is, spontaneous-talented versus non-spontaneous-talented, and (3) To assess performance level perception in these same subjects before and after the practice period. In addition, post-practice performance of the novices was compared to expert gymnasts. Improvements due to practice were hypothesized; however, within the novice cohort, those subjects with spontaneous talent for this task were expected to experience larger improvements in performance than those less talented. Similarly, perception of performance level will be closer to objective estimates in those subjects with spontaneous talent after the practice period. In addition, it was hypothesized that improvements in performance will be revealed by the closer adjustment in the novice group to the events and path of the expert gymnasts' hip and shoulder functional phases.

Method

Participants

Two cohorts were used in this study: Novice and expert. Twenty-five college-age students (fifteen males and ten females, age= 20.2 (±2.2) years; height=1.70 (±0.07) m; mass=66.5 (±11.7) kg) took part in the study as the novice cohort. While involved in sports activities, participants in the novice cohort were recruited based upon the condition that swinging on high bar in gymnastics presented a completely novel task for them. These 25 participants were classified using a k-means Cluster analysis (Systat 11.0, Systat Software, Inc., San José, CA, USA) into two skill groups: non-spontaneous-talented (NST, 8 males and 7 females) and

[redacted]

spontaneous-talented (ST, 7 males and 3 females): on the basis of their best performed swing during the first trial in the first practice session (Table 1). An additional expert group (E) was made up of nine gymnasts from the national team (six males and three females, age= 19.0 (±4.5) years; height=1.59 (±0.13) m; mass=54.9 (±15.3) kg), who had more than 5 years of experience in gymnastics' competition and an average of ten training sessions per week (Table 1). All experts were able to perform the longswing (basic element in gymnastics) at top level, that is, without any FIG Code of Points' penalty. All participants were fit and injury free and each signed a consent form to participate in the study. The study was approved by the local ethics committee.

TABLE 1

The task

For the purpose of analysis, we divided the longswing on the high bar into three phases independently for hip and shoulder angle joint movements in the sagittal plane, and defined instants of interest (events) within each phase (Fig. 1b):

1) Preparation phase (P1-P2), which includes the path between smallest angle during downswing and largest angle after that. The events analyzed in this phase are the minimum angle of the hip (P1H) and shoulder (P1S) during downswing, and maximum angle of the hip (P2H) and shoulder (P2S).

2) Principal phase (P2-P3), which includes the path between largest angle from position 2 and smallest angle during upswing. The events analyzed in this phase are the maximum angle of the hip (P2H) and shoulder (P2S), and minimum angle of the hip (P3H) and shoulder (P3S) during upswing.

3) Final phase (P3-Pf), which includes the percentage of path between smallest angle during upswing and the end point of the swing (Pf). The events analyzed in this phase are the path from minimum angle of the hip (P3H) and shoulder (P3S) during upswing.

FIGURE 1

Movement performance was inferred from the maximum elevation on the downswing, initial position (Pi), the maximum elevation on the upswing, final position (Pf) , the total path of the swing amplitude, and all previously defined swing events and phases (Fig 1b).

Experimental protocol

The experiment was carried out in a covered gymnasium on a regular high bar (2.60 m from top of the mat) with two landing mats (4 x 2 x 0.2 m).Training straps were used to attach the participants' hands to the bar to reduce emotional distress and increase security (Fig. 2a). In addition, to avoid blisters and allow more practice time, the participants gripped a plastic tube that covered the bar (see Fig. 2a). At the starting position, the participants were suspended in a stationary extended position under the bar. Following, the participants were asked to perform the initial swings stressing the importance of initiating the swing trial by bending at the hip level the straight lower limbs over the trunk, and subsequently from this position, extending the whole body up to rise the CM. In order to maintain the same friction conditions between the hands and bar across all groups, the expert gymnasts also used the training straps and the plastics tubes to perform the longswings.

FIGURE 2

The task was practiced during 18 training sessions, with approximately 20 minutes/session of real practice time per participant. Two sessions took place per week. At the beginning of the first session one of the experimenters taught participants how to perform a swing on the high bar through graphical and verbal explanation of the events and phases and proceeded to demonstrate it. The participants were requested to perform ten complete swings per trial. An average of 5 trials was performed per participant each session (range 6-4). To assess their perception of their own level of performance, participants drew a sketch of five of their swing events (Pi, P1H, P2H, P3H and Pf; similar to what is shown in Fig.1b) at the end of the first trial of session 1, and again at the end of the last trial in the last session to assess their perception of performance's level. An expert gymnastics trainer provided verbal feedback about the swing events and phases performance to participants during the execution of repetitions and at the end of the trial.

Data collection

Data were collected for the first trial during session 1 and the last trial during session 18, and the swing with the greatest amplitude of these first and last trials were selected for analysis. The participants were filmed with two digital video cameras at a height of 1.37 m (Handycam DCR-HC23E Mini DV, SONY, Japan) located on the participant's right side describing an angle of 90 degrees between their optical axes (Fig. 2b). The space was calibrated using a frame of known dimensions placed under the high bar before participants' performance (absolute mean reconstruction error=1.71 cm; RMSE=0.61). This calibration partially covered the area of interest, but a larger frame covering the space above and under the bar presented logistic problems in the selected venue. To assess the error embedded in a partial calibration, a different venue was utilized to analyze the swing movement in three expert gymnasts using both calibration frames. The new calibration frame was twice as tall (2 x 2 x 4.65 m) as the frame used in this study. When both calibrations were used and the longswing movement analyses were compared, the global average error was RMSE=2.5 cm, NRMSE=3.38%. Given the relatively low global average error (Angulo & Dapena, 1992; Hinrichs & McLean, 1995), the logistic problems, and the fact that most novices barely surpassed the horizontal plane at the bar height in their down- and up-swing, we deemed adequate the use of the "small" frame in this study. In fact, Hinrichs & McLean (1995) also concluded that an extrapolation of up to 100% of the calibrated space is acceptable to conduct biomechanical analyses. A reference system was defined with the Y axis as the high bar, the vertical axis as the Z, and the axis perpendicular to this plane as the X (Fig 2b).

Data reduction

The videotaped images captured at a sample rate of 50 Hz were manually digitized by the first author with Ariel Performance Analysis System (APAS System, Inc) and Kwon3D 3.00.033 (Young-Hoo Kwon & Visol, Inc). The intra-coder reliability achieved an average of RMSE=2.3 cm when the longswing of 3 participants were reanalyzed. An 18 landmarks body model was utilized with markers located on the middle of the grasping hand, wrist, elbow, shoulder, great trochanter, femoral condyle, lateral malleolus and tip of the foot bilaterally, and vertex and sternum. Raw data were smoothed using a Butterworth Low-pass fourth order recursive filter (Winter, 1990). Cut-off frequency was set at 5 Hz based on a residual analysis and qualitative evaluation of the data (Giakas & Baltzopoulos, 1997; Winter, 1990). Hip and shoulder angles in the sagittal plane were computed. Angular movements at the hip were derived from the angle between the right thigh and trunk (shoulder, great trochanter and femoral condyle markers) and movements at the shoulder from the angle between the right upper arm and trunk (elbow, shoulder and great trochanter markers). In addition, a custom software developed in Matlab version 7.01 (Mathworks R14) identified peaks and valleys in the joint angle displacement-time traces.

Body position angle was defined as the angle formed by the line connecting the greater trochanter with the middle of the grasping hand and the vertical (z-axis) of the coordinate system (Arampatzis et al., 1999) (Fig. 1a). Because using the trochanter to estimate body position in the stroke could lead to over- or under-estimation, an alternative method could be the use of the center of mass (CM). Nevertheless, the perception of the CM position is very difficult while using the trochanter to estimate body position affords good perception. Because we included perceptual assessments of initial and final body position and hip events via the sketches, we preferred the relative body position using the trochanter point.

Variables

The amplitude of the pendular oscillations of the body position (swing amplitude) was the main index of the efficacy of performance. Swing amplitude was normalized, with the 0 degrees of body position angle defined as -100% and the 180 degrees of body position defined as 0% and the 360 degrees of body position defined as 100% (Fig. 1a). The minimum percentage of the path, maximum elevation on the downswing, and the maximum percentage of the path, maximum elevation on the upswing, of each trial defined the start (Pi) and end points (Pf), respectively. We analyzed the hip and shoulder angle joint movements during the swing. Flexion and extension were measured in the sagittal plane.

Goodness of perception was evaluated by the difference between participants' perception and performed relative body position of the events Pi, P1H, P2H, P3H and Pf. Values closer to zero showed more accuracy in swing perception. Perceptions of relative body and hip positions were determined from the participants' sketches and expressed as percentages.

Statistical Analyses

To address the main purposes of the study, that is, changes between pre- and post-practice of the NST and ST groups for both motion and perception dependent variables, we used 2 (Group) X 2 (Time) mixed ANCOVAs in which group was the between-participants factor, time (first and last trial) the within participants factor, and sex was the covariate. Planned comparisons between pre- and post-practice within each group were used. In addition, NST vs. ST group effect on the magnitude of changes (post- minus pre-practice) were examined using students' *t*-tests for all variables. To address the secondary goal of this study, one-way ANCOVAs with Tukey multiple comparisons post hoc were used only on the motion dependent variables to establish differences between the NST, ST and Expert groups at the last trial.

Sex (male and female) was included as the covariate in all statistical tests. Statistical significance was set at p<.05 level. P adjustments were conducted to control for multiple comparisons when appropriate.. All tests were performed with Systat 11.0 (Systat Software, Inc., San José, CA, USA) and SigmaStat 3.1 (Systat Software, Inc., San José, CA, USA).

Results

Swing performance

Non-spontaneously talented (NST) vs. spontaneously talented (ST)

Task performance was inferred from the percentage of initial position (Pi), final position (Pf) and total path of the swing amplitude so that larger numbers meant better performance

(Table 1). The 2x2 ANCOVAs on Pi, Pf and swing amplitude revealed that there were significant group and trial (time) main effects in the three performance variables (Table 2). The interaction effects were not significant for any of these three variables. The covariate sex was not significant. Simple main effects indicated that the post-and pre-practice values were significantly different within each group for all variables (for Pi: NST group (t = 4.997, p = .000) and ST group (t = 2.576, p = .034) (Fig. 3a); for Pf: NST group (t = 5.495, p = .000) and ST group (t = 2.794, p = .020), and for swing amplitude: NST group (t = 5.586, p = .000) and ST group (t = 2.861, p = .018) (Fig. 3b)). Although differences between the novice groups decreased with practice, examining pre-to-post magnitude of change yielded no differences between the NST and ST groups (t-test of the differences).

Novices vs. Experts (3 groups)

The One-way ANCOVA at post-practice yielded significant differences between the experts and novice participants for all three variables (Table 1). The covariate sex was not significant in these tests.

Overall, these results suggest (1) novice participants improved their performance due to practice independent of group membership, and (2) novice group differences remained relevant across time.

TABLE 2 and FIGURE 3

Swing events

Non-spontaneously talented (NST) vs. spontaneously talented (ST)

[redacted]

We conducted 2x2 ANCOVAs for each swing event to investigate which parameters evolved differently between the groups. These analyses revealed that there were significant group main effects on P1H, P2H and P1S; a trial (time) main effect on P1H; and a 'group by time' interaction on P1H, P2H and P2S (Table 2). For the P2 variables, the NST group tended to deviate from experts more while the ST group migrated slightly towards the experts (Fig. 3d). Indeed, simple main effects only showed significant differences between post- and pre-practice in the NST group for (P1H (t = 6.007, p = .000) (Fig. 3c), P2H (t = 3.090, p = .010) (Fig. 3d), and P1S (t = 6.007, p = .000)) (see Table 1 for *M* and *SD* details). In contrast to P2 events, changes in P1 swing events (both hip and shoulder) for NST signified improvements since they became closer to reference values, in this case values of the Expert group. When the pre- and post-practice magnitudes of the change were compared with student *t*-tests , significant differences existed between the NST and ST groups on P1H ($F_{1,22}$=4.46, p=.046), P2H ($F_{1,22}$=8.87, p = .007) (Fig. 3d) and P2S ($F_{1,22}$=6.58, p = .018).

Novices vs. Experts (3 groups)

Examining group differences at post-practice, the One-way ANCOVAs pointed out the differences between expert and novice for all events except P2S. NST remained significantly different from experts on P1H (p = .012), P2H (p=.000), P3H (p = .000) and P3S (p=.000) (Table 1). Similarly, the ST group was significantly different from the Expert group for P2H (p=.003), P3H (p = .000) and P3S (p=.000) (Table 1). The covariate sex was significant for P3S ($F_{2,30}$=4.384, p=.045).

All together, these results indicate novice changes occurred mainly in the downswing (-100-0%) with no adjustments in P3 events. In addition, P2H and P2S changed differently depending on novice group membership with the NST group performing worse from pre- to post-practice. Lastly, P3S occurred earlier for males than females for novices and experts.

Swing phases

Non-spontaneously talented (NST) vs. spontaneously talented (ST)

The 2x2 ANCOVAs showed group effects on P3H-Pf and P3S-Pf and time effects on P1H-P2H and P3S-Pf (Table 2). There were also significant interaction effects between group and time on P2H-P3H. For P2H-P3H, the ST maintained the same value while the NST improved this phase with practice. Simple main effect indicated significant differences between post- and pre-practice for the NST group on P2H-P3H ($t = 2.825$, $p = .020$) (Fig 3f) and P3H-Pf ($t = 4.813$, $p = .000$) and for the ST group on P1H-P2H ($t = 3.227$, $p = .008$) (Fig 3e) (see Table 1 for *M* and *SD* details). Besides these results, sex and 'sex by time' were significant for P3S-Pf (Table 2). The male participants improved their performance of P3S-Pf significantly after practice ($t=3.062$, $p=.012$) while the female participants had similar values. As for the magnitude of change from pre- to post-practice, independent t-tests showed significant differences between NST and ST groups on P2H-P3H ($F_{1,22}=4.93$, $p = .037$) (Fig 3f). Sex covariate was significant for P3S-Pf ($F_{1,22}=4.94$, $p=.037$).

Novices vs. Experts (3 groups)

The One-Way ANCOVAs after practice yielded significant differences between NST participants and expert gymnasts for all phases except on P2H-P3H and P2S-P3S. On the contrary, ST participants were similar to the expert group on shoulder phases during the longswing (Table 1). The sex covariate was significant only for P3S-Pf ($F_{2,30}=9.44$, $p=.002$).

In short, these findings suggest different modifications by group in phases so that the NST group lengthened P2-P3 due to P2 being earlier, while the ST group improved P1-P2 due to an earlier P1. Both groups improved P3-Pf due to later Pf. Finally, males increased more the P3S-Pf than the females due to their earlier P3S. For the same reason, males showed the largest P3S-Pf compared to females when all groups (novices and experts) were considered.

Swing perception

Non-spontaneously talented (NST) vs. spontaneously talented (ST)

We conducted 2x2 ANCOVAs for each swing perception variable. A group main effect was observed for the pP3H and a significant 'group by time' interaction was found on pPi, pP1H and pP2H (Table 2). The covariate sex was not significant for all swing perception variables. The ST group improved perception of pPi and pP1H with practice while the NST group remained relatively constant or worsened over time. For the pP2H the NST saw a decrease in perception accuracy whereas the ST group showed a relative improvement. Simple main effects between post- and pre-practice showed significant improvements for the ST group on pPi ($t = 2.885$, $p = .008$) (Fig. 4a) and pP1H ($t = 3.117$, $p = .005$) (Fig. 4b), and a significant decrement for the NST group on pP2H ($t = 2.891$, $p = .016$) (Fig. 4c) (see Table 1 for *M* and *SD* details). When examining pre-to-post magnitude of change, we found significant differences between both groups on pPi ($F_{1,22}=7.39$, $p = .013$) (Fig. 4a), pP1H ($F_{1,22}=13.43$, $p = .001$) (Fig. 4b) and pP2H ($F_{1,22}=7.92$, $p = .010$) (Fig. 4c). Sex was not significant in any case. In summary, perception of hip performance and swing events were significantly different by group in the downswing, with only ST participants improving their perception.

FIGURE 4

Discussion

The main aim of this study was to describe performance changes in the acquisition of a novel task (swing on high bar) due to practice and initial talent. Changes in movement performance may be impacted not only by the amount and the quality of practice individuals may accumulate but also by their a-priori talent (Delignieres et al., 1998; Teulier & Delignieres, 2007). A two-month practice period resulted in an increase in swing amplitude by placing the initial and final events close or beyond the top half of the cycle. Several authors have also shown improvement due to practice in pendular oscillations' amplitude in other swing skills: in parallel bars (Delignieres et al., 1998), lateral swing on a suspended platform (Teulier et al., 2007), and swing on a ski apparatus (Vereijken, Van Emmerik, Bongaardt, Beek, & Newell, 1997). Practice of the high bar swing in novices had no effects on the upswing variables. In contrast, maximum flexion of the hip and shoulder in the downswing became closer to the half-way point (-50%), therefore extending the duration of the preparation phase (P1-P2). Improvements in the downswing compared to upswing may be facilitated by differential constraint demands. During the downswing better visual references and gravitationally assisted body displacement occurs. Similar, Delignières et al. (1998) also found significant improvements in the downswing compared to the upswing in parallel bars, a task with comparable gravitational demands.

Despite the observed improvements found in our study after the practice, novices' level of performance, event placements, and phases were not close to expert values. Previous researchers have proposed two functional phases as critical elements of skilled high bar swing (Arampatzis et al., 1999; Hiley et al., 2003; Irwin et al., 2005; Irwin et al., 2007a; Irwin et al., 2007b; ; Yeadon et al., 2000). After practice, the novice cohort was able to extend the shoulder functional phase (P3S-Pf) due to delaying the final event. Despite the improvement in the Pf, females maintained the same values for P3S-Pf phase due to their delayed shoulder flexion (P3S) while males performed an earlier P3S and increased Pf. These modifications, however, were not effective because shoulder extension occurred below 50% in the upswing. As a consequence neither males nor females performed the pushing action in the appropriate place. In contrast, the hip functional phase (P2H-P3H) was not different amongst either novice or expert groups, nor affected by practice. Similar P2H-P3H durations do not imply necessarily an improvement because placement of the phase within the cycle seemed to be more related to global outcome than phase duration. The experts placed the initiation of this phase in approximately -8%, and had the best result. In contrast, novice groups who had a smaller overall performance, initiated this phase around -26% and -25% for the NST and ST respectively. Initiating P2H-P3H so early and maintaining the same duration means that the decrease in inertial momentum by maximally flexing the hip (P3H) will also occur too early in the upswing, limiting the subsequent contribution of the shoulder functional phase to maintain angular velocity. Given these results, we would argue that in the early stages of learning, placement of the functional phase within the cycle is more critical than duration of the phase per se. In fact, spatial aspects of the performance such as hip and shoulder angular displacements of novices and experts were similar before and after practice, while their temporal characteristics demonstrated practice and novice versus expert effects. Similarly, Mazyn et al (2007) observed initial practice effects in ball catching by a novice group due to changes in spatial characteristics of their performance (ex: hand placement). On the contrary, temporal characteristics improved towards the end of the practice period. Perhaps, this is the reason why experts in this study ensured the temporal accuracy of P3 as demonstrated by a low variability in these events. None of the novice groups learned the critical events of the upswing, that is, maximal flexion of hip (P3H) and shoulder (P3S). The consistency of P3H for the experts together with their execution of P3S after +50% of the Stroke may be critical for a skilled swing.

Clearly the amount of practice accumulated by the expert cohort plays a major role in these results. Interestingly, novice performance variables (Pi, Pf and swing amplitude) were not different by spontaneous talent level (NST vs. ST), but their events and phases differed when examining the practice effects within each group. A unique consideration included in this research was the treatment of the data clustering by the individual's initial conditions on first time skill performance. It was hypothesized that within the novice cohort, participants with spontaneous talent would experience larger improvements than those less talented. However, our performance variables did not support our hypothesis while event and phase variables yielded significant interaction effects.

The event P2 critically differentiated the two groups. The ST group maintained or slightly changed the hip (P2H) and shoulder (P2S) maximum extension while the NST group began the study with P2 values closer to experts than the ST group. However, the P2H and P2S events became worse with practice for the NST group. These P2 changes impacted differently the phases (P1-P2 and P2-P3) in the novice groups. Thereby, the ST group enlarged the preparation phases (P1-P2 by hip and shoulder) because after practice they increased the P1 events but maintained P2 in a similar swing amplitude percentage. On the other hand, the inappropriate advancement of the P2 and the maintenance of P3 after practice produced extended P2-P3 phases in the NST group.

The ST vs. NST group differences in P2 could be partially explained by group differences found in perceptual changes due to practice. Motor learning has been proposed to also depend on the ability to correctly perceive the environment (Hatzitaki et al., 2002). Furthermore, several authors (Handford, Davids, Bennett, & Button, 1997; Hatzitaki et al., 2002; Nourrit et al., 2000) consider movement learning as a motor-perceptual workspace where the changes in one domain affect the other, and vice versa. Thereby, practice can affect both, performance and perception at the same time. An additional objective of this research was designed to measure changes in the participants' performance level perception after practice. Our results showed that the perception of performance and hip events in the downswing (Pi-P2H) improved only in the ST group. In contrast, the NST group worsened their perception of the same parameters with practice, despite having a more accurate initial perception than the ST group. Therefore, the ST group improved perception of the initial position (pPi) and the timing of hip maximum flexion in downswing (pP1H) at the same time that they achieve better Pi and P1 events, while maintaining the same temporal relationship for P2 (i.e. closer to the bottom of the cycle). Conversely, the NST group was not able to perceive changes on Pi, P1H and P2H after practice, perhaps due to a lesser motor-perceptual mapping.

Our results are in partial agreement with Hecht, Vogt, and Prinz (2001) who found transference from both performance to perception and perception to performance in cyclical arm movements indicating a bidirectional relationship between performance and perception. In our study, evidence for transference from performance to perception in the learning of the swing on high bar was only found in the ST group.

Several factors involved in the practice effects could explain the motor-perceptual differences between ST and NST groups. These factors can be categorized as environmental, organismic, and task constraints (Clark, 1995; Newell, 1986; Nourrit et al., 2000). In this study, the task constraints constituted standardized complexity and difficulty of the task and the same biomechanical characteristics of the pendulum for all participants. Therefore, we would argue that task constraints do not help to explain group effects. Within the environmental constraints, the feedback provided to the participant, and the changes in visual reference during the swing could be considered. The visual reference changed from a familiar situation in the downswing (for example, they saw the floor, poles and cables of the high bar) to an unfamiliar perspective where they saw the ceiling. Within the organismic constraints, one may include the proprioceptive, visual, and vestibular sensory systems, and ways to process or utilize self-generated feedback while performing the skill.

We propose that the improvements in the downswing performance for both novice groups were mainly related to the familiar visual reference in combination with proprioceptive feedback. The participants reached the maximum velocities at the transition from down- to up-swing overlapping with the changes in visual reference, and therefore, increasing performance and perception demands at P2. Such increment in difficulty had different effects between novice and experts. The experts showed high variability at P2 because they can modify the intensity and enlargement of the P2-P3 phases to achieve the optimal P3.

Although the true process of learning cannot be characterized, our study design let us describe the changes occurred from the initial to the last session. In addition, while the analysis of the skill allowed us to present a proposal of potential constraints to explain performance improvements, speculation of potential causes of improvements in swing perception by the ST group are more difficult. In this study, the swing perception was only assessed by global variables, that is, perceived relative body and hip positions. These variables did not allow a direct test of different sensory modality contribution to motor-perceptual mapping. Further studies are necessary to assess the complete process of learning and the influence of each perceptual factor in the swing learning.

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Figure Captions:

Fig. 1. In (a), swing normalization and body position angle (α) defined by the z axis, middle grasping hand (1) and greater trochanter (2) landmarks. In (b), initial position (Pi), final position (Pf) and swing events (P1, P2, and P3) from hip (H) and shoulder (S) movements. For simplicity, H and S events have been represented at the same instant of time for P1-P3.

Fig. 2. Schematic illustration of the experimental setup: (a) plastic tube that covered the bar (1), training straps (2), and participant's hands attached to the high bar and gripped to the plastic tube (3); (b) high bar (1), frame of 2x2x2 m (2); camera locations (3), and reference system (x, y and z axis).

Fig. 3. Results of two (Group) x two (Time) ANCOVA with repeated measures comparing pre- and post-practice values of the (a) Pi, (b) swing amplitude, (c) P1H, (d) P2H, (e) P1H-P2H, and (f) P2H-P3H. The expert mean (E) on these variables are provided for comparison, (✱) significant group differences and closer to (E) and (✱ in circle) significant group differences and further from (E). In addition, significant results of the student's t-tests comparing magnitudes of the change between pre- and post-practice for NST and ST groups are indicated with (●).

Fig. 4. Results of two (Group) x two (Time) ANCOVA with repeated measures comparing pre- and post-practice values of the (a) pPi, (b) pP1H, and (c) pP2H. Values closer to zero showed more accuracy in swing perception. (✱) significant differences and closer to zero and (✱ in circle) significant differences and further to zero.. In addition, significant results of the student's t-tests comparing magnitudes of the change between pre- and post-practice for NST and ST groups are indicated with (●).

Table 1

K-means Cluster analysis, participant characteristics, pre- and post-practice swing variables means (M) and standard deviations (SD), and results of post-practice One-Way ANCOVA with sex included as the covariate. Tukey's Method multiple comparison post hoc was performed.

	Pre					Post							
	Cluster	NST (*n* = 15)		ST (*n* = 10)		NST (*n* = 15)		ST (*n* = 10)		E (*n* = 9)		ANCOVA	
	p	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	p	Post-hocs
Participants													
Age (years)	-	19.95	1.99	20.67	2.64	-	-	-	-	19.00	4.47	-	-
Height (m)	-	1.70	0.07	1.71	0.08	-	-	-	-	1.59	0.13	-	-
Mass (kg)	-	66.51	13.38	66.37	9.21	-	-	-	-	54.88	15.29	-	-
Swing Perfomance [a]													
Pi	.002	-42.30	8.02	-52.74	7.29	-54.45	9.58	-61.04	12.15	-99.34	0.53	.000	NST and ST >E
Pf	.002	39.90	8.28	49.49	7.74	52.09	8.60	58.06	10.43	99.24	0.67	.000	E>ST and NST
Swing amplitude [b]	.002	82.20	15.72	102.23	14.78	106.53	17.63	119.09	22.46	198.58	0.93	.000	E>ST and NST
Swing Events [a]													
P1H	.001	-39.89	11.71	-52.70	7.35	-54.43	9.58	-60.39	11.88	-69.45	14.28	.005	NST>E
P2H	.001	-17.59	9.49	-26.36	5.09	-29.88	8.78	-25.45	9.71	-7.95	12.97	.000	E>ST and NST
P3H	.691	19.37	6.36	18.41	5.92	17.82	12.82	19.71	13.29	39.09	5.25	.000	E>ST and NST
P1S	.002	-34.83	13.74	-43.09	16.94	-53.88	9.67	-57.55	13.64	-62.00	18.45	.031	-
P2S	.000	-10.70	9.07	-19.02	14.57	-31.59	7.94	-23.67	10.83	-9.33	14.23	n.s.	-
P3S [b]	.839	31.62	8.27	34.50	10.39	32.35	9.55	34.48	9.06	61.82	6.87	.000	E>ST and NST
Swing phases [a]													
P1H-P2H	.563	22.29	6.62	26.34	9.23	24.54	12.91	34.95	9.45	61.50	11.00	.000	E>ST and NST
P2H-P3H	.057	36.96	11.29	44.78	6.40	47.70	14.80	45.16	20.63	47.04	11.42	n.s.	-
P3H-PfH	-	20.53	9.80	31.08	9.43	34.26	10.44	38.35	7.30	60.15	5.17	.000	E>ST and NST
P1S-P2S	.702	24.13	9.96	24.08	14.03	22.29	11.23	33.88	10.80	52.67	16.85	.000	E>NST
P2S-P3S	.000	42.32	9.08	53.52	16.90	63.95	14.31	58.15	14.17	71.15	14.13	.033	-
P3S-PfS [b]	-	8.28	8.98	14.99	14.47	19.73	11.23	23.58	12.64	37.42	6.52	.001	E>NST
Perception Swing [a]													
pPi	-	-9.08	7.29	-10.52	9.33	-10.22	6.40	-0.87	6.32	-	-	-	-
pPf	-	6.31	7.06	5.86	10.24	7.75	9.70	0.72	6.35	-	-	-	-
pP1H	-	-7.44	10.52	-14.15	10.39	-14.54	9.87	-2.84	8.28	-	-	-	-
pP2H	-	-8.56	12.70	-20.62	9.00	-25.27	13.26	-17.39	13.57	-	-	-	-
pP3H	-	-8.07	11.53	-17.51	13.30	-18.96	14.07	-22.62	16.58	-	-	-	-

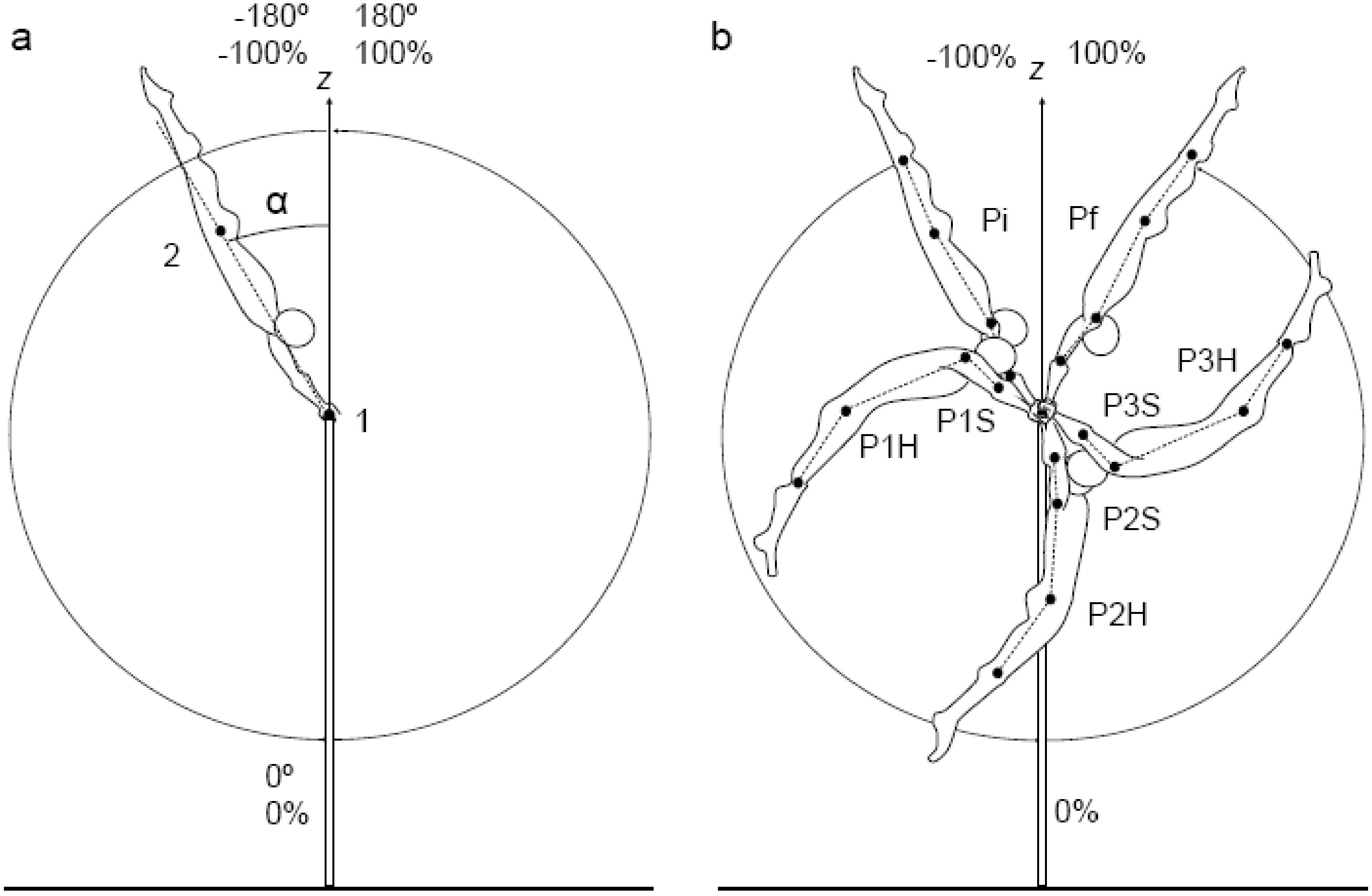
[a] All values in percentage of stroke's swing

[b] Sex showed significant differences.

Table 2
Significant results of two (Group) x two (Time) ANCOVA with repeated measures. Sex was included as the covariate.

Variable group	Variable name	Main effects and interaction	F	Degrees of freedom	p	Power
Performance	Pi	Group	8.31	1,22	.009	.79
		Time	13.12	1,49	.002	.93
	Pf	Group	8.86	1,22	.007	.81
		Time	6.36	1,49	.019	.67
	Stroke	Group	8.79	1,22	.007	.81
		Time	10.97	1,49	.003	.89
Swing events	P1H	Group	7.39	1,22	.013	.74
		Time	6.64	1,49	.017	.69
		TimexGroup	4.46	1,22	.046	.52
	P2H	TimexGroup	8.86	1,22	.007	.81
	P1S	Group	9.24	1,22	.006	.83
	P2S	Group	13.46	1,22	.001	.94
		TimexGroup	6.59	1,22	.018	.69
Swing phases	P1H-P2H	Time	5.18	1,49	.033	.59
	P2H-P3H	TimexGroup	4.93	1,22	.037	.57
	P3H-Pf	Group	8.35	1,22	.008	.79
	P3S-Pf	Group	5.12	1,22	.034	.58
		Sex	4.53	1,22	.045	.53
		Time	7.78	1,49	.011	.76
		TimexSex	4.94	1,22	.037	.57
Perceptive	pPi	TimexGroup	7.39	1,22	.013	.74
	pP1H	TimexGroup	13.43	1,22	.001	.94
	pP2H	TimexGroup	7.92	1,22	.010	.77
	pP3H	Group	5.58	1,22	.027	.62

Figure 1



a
-180º
-100%
180º
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α
2
1
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Pi
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Figure 2

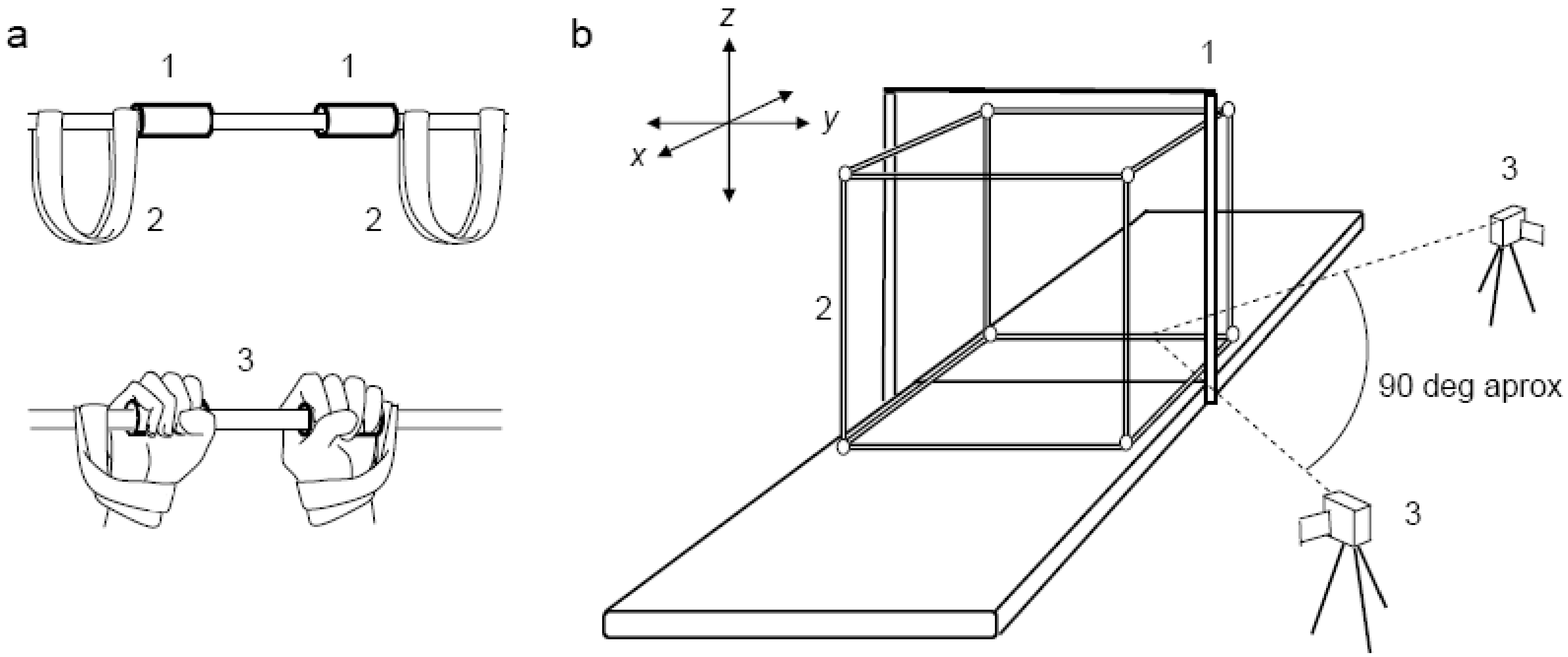
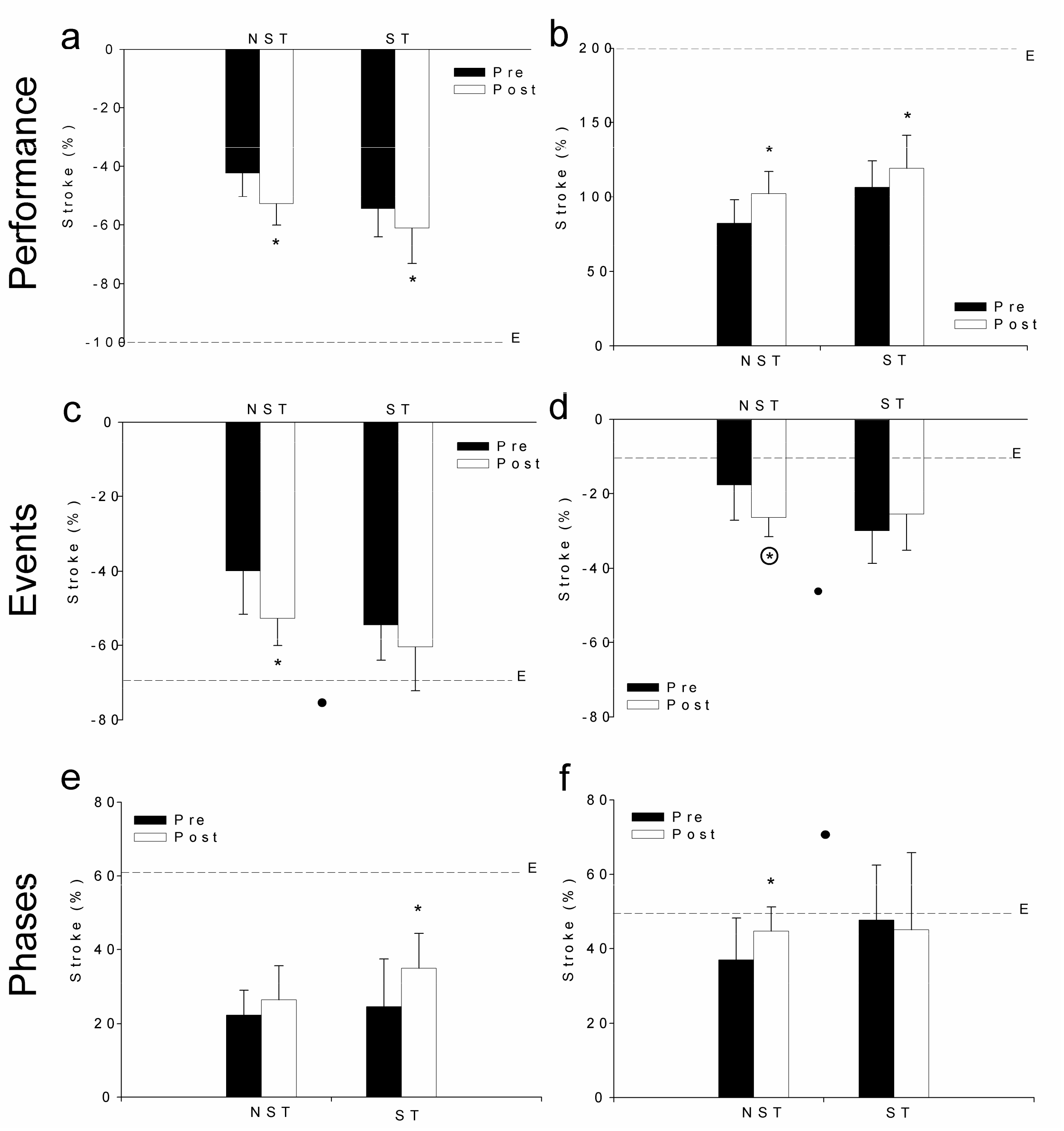


Figure 3


Performance
Events
Phases
a
b
c
d
e
f
NST
ST
Pre
Post
Stroke (%)
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200
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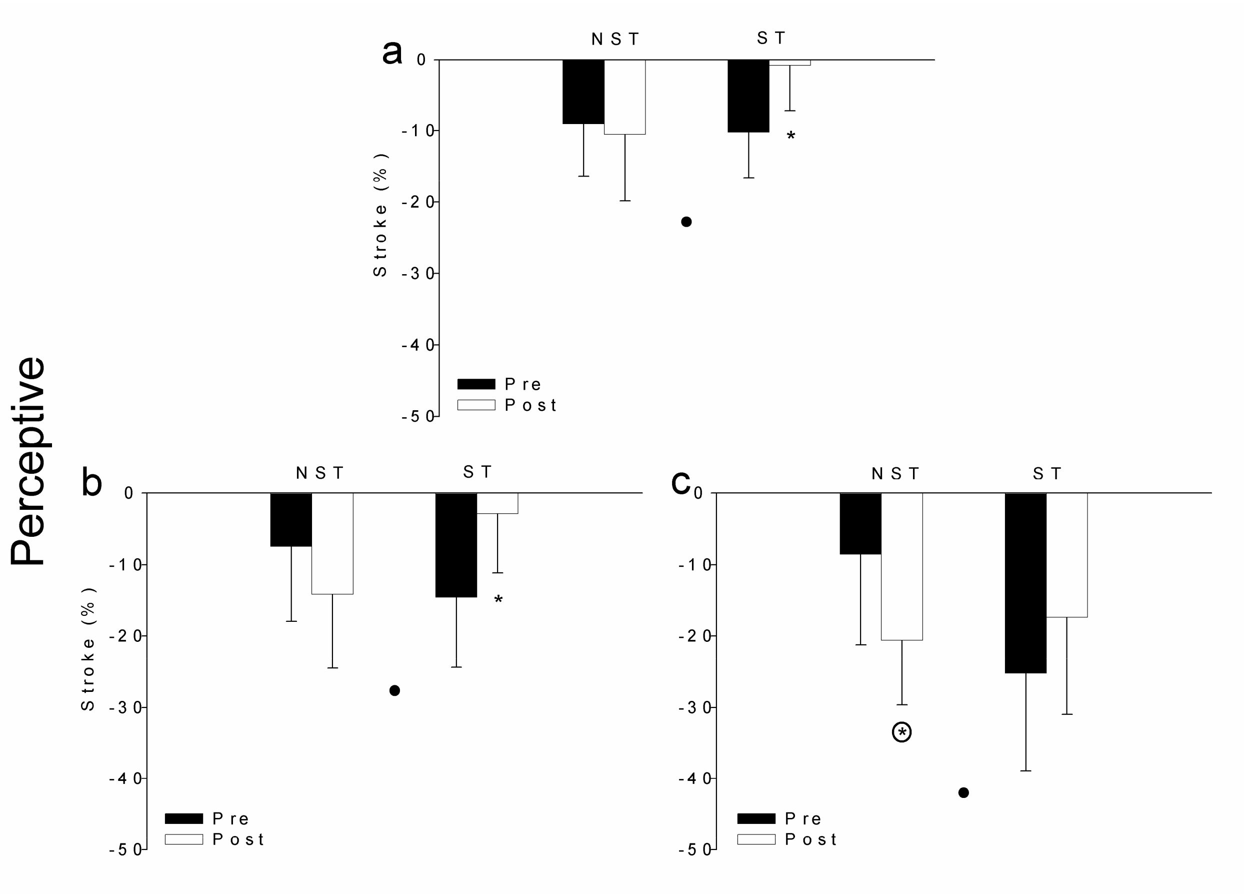
80

Figure 4



Chapter 5. Coordination analysis reveals differences in performance strategies for the swing high bar in novice adults

Sports Biomechanics (second submittion)

Coordination analysis reveals differences in performance strategies for the swing high bar in novice adults

Key words: continuous relative phase, expert gymnasts, practice, talent, variability

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Abstract

Adequate coordination between hip and shoulder is important for effective longswing functional phases. This research describes inter-joint coordination changes after a practice period of the swing on high bar in a novice cohort, divided by initial skill level (i.e. talent) into two groups: spontaneous-talented, (ST, n=10, closer to expert performance) and non-spontaneous-talented (NST, n=15). Division was accomplished using a k-means Cluster analysis. Additionally, post-practice swing performance was compared to expert gymnasts (n=9). Swing amplitude, hip-shoulder coordination, and its variability were assessed for the pre- and post-practice sessions. ANCOVAs showed similar practice effects in swing enlargements for the ST and NST, 11% and 18% respectively, but inter-joint reversal points (time lag between contiguous joints' events) in the downswing were different. The ST group paired both joints during downswing (events P1 and P2) closer than the NST group due to practice. In addition, the ST group increased intra-subject variability in P2 but not P1. Initial talent could help to achieve the right temporal sequence in both P1 and P2, which would allow the exploration of coordination patterns at P2. However, and despite of initial skill level, upswing performance will required more finely tuned coordination, and therefore, more focused practice.

Word Count: 196

Introduction

The majority of gymnastic movements on the high bar belong to a group of rotations in the vertical plane around a horizontal axis (Brüggemann, Cheetham, Alp, and Arampatzis, 1994). The longswing is a gymnastic element in which the gymnast goes from handstand to handstand position through rotation around the high bar with a straight body (Hiley and Yeadon, 2003). Because of the longswing's association with the development of more complex high bar movements, the coaching literature has identified the 'regular' or traditional backward longswing as a key skill (Hiley et al., 2003; Irwin and Kerwin, 2005; Irwin and Kerwin, 2007a). Full extension of arms and legs during the whole movement is required to achieve the quality standards defined by the Fédération Internationale de Gymnastique (FIG) Code of Points (2009). In addition, several studies emphasize the importance of the hip and shoulder flexion and extension for the successful execution of the swing (Arampatzis and Bruggemann, 1999; Yeadon and Hiley, 2000; Hiley et al., 2003). Two key functional characteristics of "good high bar swing mechanics" have been identified: (1) hip functional phase, a rapid hyper-extension to flexion of the hip after the gymnast passes through the lowest part of the movement (Brüggemann et al., 1994; Yeadon et al., 2000; Hiley et al., 2003; Irwin & Kerwin, 2007a; b) and (2) shoulder functional phase, flexion to extension of the shoulder joint before the highest point of the circle (Yeadon et al., 2000; Hiley et al., 2003; Irwin et al., 2007a; b). Gymnasts execute the hip functional phase in an attempt to reduce the radius between the center of mass (CM) and the rotational axis to help in the maintenance of the angular momentum (Yeadon et al., 2000; Irwin et al., 2005; Irwin et al., 2007a). On the other hand, shoulder functional phase is performed to push up the CM over the bar to continue gaining potential energy.

Although each functional phase is defined on the basis of one main joint, adequate coordination between the hip and shoulder are required to ensure the effectiveness of the functional phase. Inter-joint coordination is critical to maintain the positive balance between the angular momentum created during the downswing and the angular momentum lost in the ascending phase. Such coordination is one of the main concerns a novice individual must resolve when faced with a novel task. That is, an effective mode of coordination among the participating joints and limbs ought to be discovered (Bernstein, 1967; Temprado, Della-Grasta, Farrell, and Laurent, 1997; Stergiou, Jensen, Bates, Scholten, and Tzetzis., 2001; Hong and Newell, 2006). According to Irwin and Kerwin (2007b), coordination has been defined as the stable spatial-temporal relationship among movement system components (i.e. limb segments and joints), to achieve the task's goal. Limb segments and joints are in an in-phase coordination mode when they move in synchrony with a 0º phase lag between them, while the coordination is in an anti-phase mode when joints or segments move in opposite directions with a phase lag of 180º. However, multiple intermediate out-of-phase coordination modes exist between in- and anti-phase coordinations.

Discovering new modes of coordination may involve an individual undergoing a transition from one stable coordination to another (Handford, Davids, Bennett, and Button, 1997; Temprado et al., 1997). Stable forms of coordination show low variability and represent behavioral states that are reproducible and independent of each other; while high variability is characteristic of a system in transition (Clark and Phillips, 1993; Clark, 1995; Hamill, van Emmerik, Heiderscheit, and Li, 1999). Higher within subject variability of coordination in similar conditions could reveal transition phases in learning (Clark et al., 1993; Clark, 1995; Hamill et al., 1999). On the other hand, lower values of within subject variability could be related to the demands of the movement such as the distance of an accurate throw (Barlett, Wheat, and Robins, 2007) or the swimming speed (Nikodelis, Kollias, and Hatzitaki, 2005). Certain amount of within subject variability in the coordination is also essential to establish the necessary combination of stability and flexibility to adapt movement to a specific context (Hamill et al, 1999; Davids, Glazier, Araújo, and Bartlett, 2003).

The impact of contextual demands on performance variability has also been measured by inter-individual variability as suggested by Nourrit et al. (2000) in a sky learning paradigm by increasing apparatus restrictions. In order to produce efficient movement, consistency will be found in the critical events or functional phases of that movement. For example, Koeing et al. (1994) found that golfers regardless of their skill level decrease variability of force production from the mid-point of the downswing to the impact phase. In addition, Fleisig et al. (2009) analyzed the variability in the baseball pitching and reported more consistency with increased skill level at the instant of foot contact, during the arm cocking and arm acceleration phases. These consistencies evidenced the importance of both, contextual demands and level of expertise to performance level. Furthermore, these examples also highlight the relevance of critical events and phases to high level performance of different movement.

Changes in coordination mode emerge from the interplay between practice and the constraints imposed on the degrees of freedom of the system associated with the individual, the task, and the environment (Kugler, Kelso, and Turvey, 1980; Newell, 1986; Thelen and Smith, 1994;Clark, 1995; 2002; Handford, Davids, Bennett, and Button, 1997; Marin, Bardy, and Bootsma, 1999; Nourrit, Deschamps, Lauriot, Caillou, and Delignières, 2000;Holt, 2005). The specific circumstances affect the impact of these three categories of constraints (individual, task, and environment) on the mode of coordination. However, practice is considered the single most important factor to induce permanent improvements in the ability to perform a motor skill (Nourrit et al., 2000; Guadagnoli and Lee, 2004).

While the amount and quality of practice individuals may accumulate will highly impact the movement learning process spontaneous talent or a-priori talent must also be taken in to consideration (Davids, Lees, and Burwitz, 2000; Elferink-Gemser, Visscher, Lemmink, and Mulder, 2007). For the purpose of this paper, learning was defined as changes in performance and coordination while talent was defined as the individual's capacity to be successful due to some developmental advantage (i.e. an individual or organism constraint). Improvements in motor skill are therefore related with the individual's pre-existing capacities making the analysis of this initial state of the system a key point for understanding motor learning (Delignières et al., 1998). In fact, different effects of practice in the performance of lateral swing on a suspended platform were found in participants who did not possess the same skill level at the beginning of practice (Teulier and Delignières, 2007). These authors suggested that these differences could arise from individual-specific organismic constraints.

A chance to assess coordination changes and variability is the learning of a new sport skill. Swing on high bar have been investigated in previous research to evaluate its optimal kinematics and kinetics characteristics (Kopp and Reid, 1980; Gervais and Tally, 1993; Kerwin, Yeadon, and Harwood, 1993; Witten, Brown, Witten, and Wells, 1994; Arampatzis et al., 1999; Yeadon et al., 2000;Hiley et al., 2003). In addition, studies have compared swing progression exercises to achieve optimal skill performance (Irwin et al., 2005; Irwin et al., 2007a; b). While improvements in coordination due to practice in gymnastics have been previously examined (Delignières et al., 1998), learning the high bar swing (performance and coordination gains) considering the a-priori talent and the practice effects has not been contemplated in previous studies.

The aim of this research, therefore, was to describe movement coordination changes and variability after a 9-weeks practice period of a novel task (swing on the high bar) in a novice cohort, which was divided in two groups considering the initial level of performance and similarity with the expert group: spontaneous-talented (more similar to experts) versus non-spontaneous talented (less similar to experts). In addition, post-practice performance, coordination and coordination variability of the novices were compared to expert gymnasts. Given the task characteristics, we focused in the inter-joint coordination between the hip and the shoulder in this study. We assumed that initial values closer to experts without previous experience represented a possible advantage to improve movement. We hypothesized that, within the novice cohort, those subjects with spontaneous talent for this task will experience larger improvements in movement performance and coordination than those less talented. In particular, it was hypothesized that swing amplitude will be larger and hip and shoulder will be more consistently and better coordinated within each functional phase in the spontaneous-talented group. Additionally, novices' performance and coordination would improve with practice making their swing more similar to experts' swing.

Method

Participants

Two cohorts were used in this study: novice and expert. Twenty-five students (fifteen males and ten females, age 20.2±2.2 years; height=1.70±0.07 m; body mass=66.5±11.7 kg) took part in the study as the novice cohort. While they were active people and usually practiced sports activities, participants in the novice cohort were recruited based upon the condition that swinging in high bar's gymnastics presented a completely novel task for them. The best performed swing for each participant was selected according to a qualitative assessment of swing amplitude by an expert gymnastics coach. The 25 participants were classified using a k-means Cluster (Systat 11.0, Systat Software, Inc., San José, CA, USA) analysis into two skill groups: non-spontaneous-talented (NST, 8 males and 7 females) and spontaneous-talented (ST, 7 males and 3 females) (Table 1), on the basis of the swing performance, events and phases values from their best performed swing during the first trial in the first practice session. An additional expert group (E) consisted of nine gymnasts from the national team (six males and three females, age 19.0±4.5 years; height 1.59±0.13 m; body mass 54.9±15.3 kg), who had more than 5 years of experience in gymnastics' competition and an average of ten training sessions per week. All experts were able to perform the longswing (basic element in gymnastics) at top level, that is, without any FIG Code of Points penalty. All participants were fit and injury free and each signed a consent form to participate in the study. The study was approved by the local ethics committee.

****Table 1 near here****

Task

To analyze the longswing on the high bar, we defined three events of interest (Arampatzis et al., 1999; Yeadon et al., 2000; Hiley et al., 2003) independently for the hip (H) and shoulder (S) angle joint movements in the sagittal plane (Figure 1): the minimum angle of the hip and shoulder during downswing (P1H, P1S) and upswing (P3H, P3S); and the maximum angle between P1 and P3 of the hip (P2H) and shoulder (P2S). These events are the actual reversal points where joint movements change from flexion to extension (P1 and P3) or from extension to flexion (P2). In addition, the time lags between contiguous events of different joint (P1H-P1S, P2H-P2S, P3H-P3S) were defined.

****Figure 1 near here****

The total path of the swing, that is the swing amplitude, was inferred from the maximum elevation of the center of mass (CM) on the downswing, initial position (Pi), and the maximum elevation on the upswing, final position (Pf) (Figure 1).

Experimental protocol

The experiment was carried out in a covered gymnasium on a regular high bar (2.60 m from top of the mat) with two landing mats (4 x 2 x 0.2 m). Training straps were used to attach the participants' hands to the bar to reduce emotional distress and increase security (Figure 2). In addition, to avoid blisters and allow more practice time, the participants grabbed a plastic tube that recovered the bar (see Figure 2). At the starting position, the participants were suspending quiet and in an extended position under the bar. To achieve the required initial angular velocity, the participants were asked to perform the initial swings of following the instructions: (1) initiating the swing trial by bending at the hip level, (2) do so by bending the straight lower limbs over the trunk to initiate the swing, and (3) subsequent to this position, extending the whole body up to rise the CM. In order to maintain the same friction conditions between the hands and bar across all groups, the expert gymnasts also used the training straps and plastic tubes to perform the longswings.

****Figure 2 near here****

The task was practiced during 18 training sessions (estimated time by expert coaches to learn the longswing in novice adults), with approximately 20 minutes/session of real practice time per participant. Two sessions per week were carried out. At the beginning of the first session one of the experimenters taught participants how to perform a swing in the high bar through graphical and verbal explanation of the events and phases. In addition, the experimenter proceeded to demonstrate the skill. The participants were requested to perform ten complete swings per trial. An average of 5 trials per session were performed by each participant (range 6-4). A new trial only started if the participant deemed him/herself completely recovered. An expert gymnastics coach provided verbal feedback about the swing events and phases performance to participants during the execution of repetitions and at the end of the trial.

Data collection

Data were collected for the first trial during session 1 and the last trial during session 18, and the swing with the largest amplitude of these first and last trials were selected for analysis. The participants were filmed with two digital video cameras at a height of 1.37 m (Handycam DCR-HC23E Mini DV, SONY, Japan) located on the participant's right side describing an angle of 90 degrees between their optical axes (Figure 2). The space was calibrated using a frame of known dimensions placed under the high bar before participants' performance (absolute mean reconstruction error=1.71 cm; RMSE=0.61). This calibration partially covered the area of interest, but a larger frame covering the space above and under the bar presented logistic problems in the selected venue. To assess the error embedded in a partial calibration, a different venue was utilized to analyze the swing movement in three expert gymnasts using both calibration frames. The new calibration frame was twice as tall (2 x 2 x 4.65 m) as the frame used in this study. When both calibrations were used and the longswing movement analyses were compared, the global average error was RMSE=2.5 cm, NRMSE=3.38%. Given the relatively low global average error (Angulo and Dapena, 1992; Hinrichs and McLean, 1995), the logistic problems, and the fact that most novices barely surpassed the horizontal plane at the bar height in their down- and up-swing, we deemed adequate the use of the “small” frame in this study. A reference system was defined with the *y* axis as the high bar, the vertical axis as the *z*, and the axis perpendicular to this plane as the *x* (Figure 2).

Data reduction

The videotaped images captured at a sample rate of 50 Hz were manually digitized by the first author with Ariel Performance Analysis System (APAS System, Inc) and Kwon3D 3.00.033 (Young-Hoo Kwon & Visol, Inc). The intra-coder reliability for the whole trajectory achieved an average value of RMSE=2.3 cm when the longswing of the participants were analyzed. An 18 landmarks body model was utilized with markers located on the middle of the grasping hand, wrist, elbow, shoulder, great trochanter, femoral condyle, lateral malleolus and tip of the foot bilaterally, and vertex and sternum. Raw data were smoothed using Butterworth Low-pass fourth order recursive filter (Winter, 1990). Cut-off frequency was set at 5 Hz based on a residual analysis and qualitative evaluation of the data (Winter, 1990; Giakas, Baltzopoulos and Barlett, 1997). The flexion – extension angle and angular velocities for the hip and shoulder in the sagittal plane were computed. Angular movements at the hip were derived from the angle between the right thigh and trunk (shoulder, great trochanter and femoral condyle markers) and movements at the shoulder from the angle between the right upper arm and trunk (elbow, shoulder and great trochanter markers). In addition, a custom software developed in Matlab version 7.01 (Mathworks R14) identified peaks and valleys in the joint angle displacement-time traces.

Body position angle was defined as the angle formed by the line connecting the CM with the middle of the grasping hand and the vertical (z-axis) of the coordinate system (Yeadon et al., 2000) (Figure 1a). We calculated the location of the center of mass from novice participants and male gymnasts using the height and body mass of the athletes and Dempster's cadaver data (Demspter, 1955), with the trunk and head separated according to Clauser's data (Clauser, McConville, and Young, 1969). The female gymnasts' CM (average age = 13.23 years) were computed using their individual ages with Jensen's equations to subjects between 4 and 20 years (Jensen, 1989; Jensen and Nassas, 1988).

Variables

To address the aims of the study, performance was defined as swing amplitude, while inter-joint coordination was assessed using four types of variables: inter-joint reversal points, mean absolute relative phase, absolute difference in the continuous relative phase, and deviation phase.

The amplitude of the pendular oscillations of the body position (swing amplitude) was the main index of performance. Swing amplitude was normalized, with the 0 degrees of body position angle defined as -100% and the 180 degrees of body position defined as 0% and the 360 degrees of body position defined as 100% (Figure 1a).

The minimum percentage of the path, maximum elevation on the downswing, and the maximum percentage of the path, maximum elevation on the upswing, of each trial defined the start (Pi) and end points (Pf), respectively. The total path between Pi and Pf was the swing amplitude.

We analyzed the hip and shoulder angle joint movements during the swing to identify the reversal points (Figure 1). In both, flexion and extension were measured in the sagittal plane. The hip and shoulders reversal points were expressed in swing's percentage. In order to characterize the coordination between the hip and shoulder in the swing in high bar, we defined inter-joint reversal points (P1H-P1S, P2H-P2S, and P3H-P3S) (previously called time lags), also as percent of swing amplitude, using the critical events for both angle joint movements of the hip and the shoulder (Figure 1). These inter-joint reversal points indicate the temporality of the hip and shoulder actions and therefore it is a measurement of temporal coordination. Values closer to experts indicate better temporal coordination.

Coordination was also assessed with the continuous relative phase (CRP). The CRP was used to represent the phasing relationships or coordination mode between the actions of the two joints at every point. Each CRP was obtained by subtracting the phase angle of the distal joint (hip) from that of the proximal (shoulder), namely $\varphi_{\text{shoulder-hip}}$ (Clark et al., 1993; Hamill et al., 1999; Irwin et al., 2007b). The angular displacement (θ) and angular velocity (ω) of each swing were normalized according to Hamill et al. (1999) to allow for the calculation of the phase angles using $\varphi=\tan^{-1}(\omega / \theta)$. In addition, the calculated phase angles were corrected to range values between 0-180º before we computed CRP.

In Figure 1, the continuous relative phase graph of an expert gymnast was depicted for a longswing in high bar. Regarding the phase angle (ordinate axis), its value was around 0º at the beginning of the movement indicating that the hip and shoulder moved in synchrony or both maintained the same angle values. This in-phase relationship became out-of-phase around -80% (mainly due to hip flexion more than shoulder flexion). Around 40% of the upswing (when the hip achieved the maximum extension,P3H) the coordination changed faster to an out-of phase mode (mainly due to the time delay between hip's and shoulder's flexion). Regarding the % swing amplitude (abscissa axis), during the P1H and P1S, the reversal point of the P1H and P1S occurred closer despite their out-of-phase. In contrast, the inter-joint reversal points P2H-P2S and P3H-P3S were relatively far apart.

Additionally to a qualitative description of the CRP graphs, mean absolute relative phase (MARP) was used to quantitatively describe and statistically test differences between relative phase curves. MARP was defined as the average of the absolute values of a selected section in the relative phase (Stergiou et al., 2001). We computed the MARP of the contiguous events of different joints (P1H-P1S, P2H-P2S, and P3H-P3S).

To assess the effect of the hip and shoulder joint actions (flexion or extension) at each reversal point (P1, P2 or P3) on the coordination mode, we examined the absolute differences in the continuous relative phase. We computed the absolute differences in the CRP by subtracting the relative phase value of the hip and shoulder events (for example, for P1 difP1H-P1S=$|\varphi_{P1H}- \varphi_{P1S}|$). A small value of the absolute difference indicated that the consecutive actions of the two joints had a small effect on coordination mode. This would be expected to occur at P1H-P1S. In contrast, the expected disassociated actions of hip and shoulder at P3 would produce a large change in coordination mode. That is, a large absolute difference of the computed CRP.

In addition, we analysed within subject variability of the coordination mode with the deviation phase (DP) (Stergiou et al., 2001). The deviation phase was the ratio between the standard deviation of the CRP values and the number of points (data) for the analyzed section of the movement. We calculated DP in the CRP sections delimited by contiguous events of different joints (P1H-P1S, P2H-P2S or P3H-P3S) to analyze inter-joint coordination within subject variability. A small DP value indicates more consistency in the coordination mode resulting from the consecutive action of the two joints. On the contrary, large values are typical in the early stages of learning in novice participants (Robertson, 2001; Buchanan, Zihlman, Ryu, and Wright, 2007).

Statistical Analyses

Continuous relative phase graphs were analyzed qualitatively for similarities and differences between groups and time. To address the main purposes of the study, that is, changes in performance and coordination between pre- and post-practice of the NST and ST group, we used 2 (Group) X 2 (Time) mixed ANCOVAs in which group was the between-participants factor and time (first and last trial) the within-participants factor, and sex was the covariate. Post-hoc comparisons between pre- and post-practice within each group were used. In addition, NST vs. ST group effect on the magnitude of changes (post- minus pre-practice) were examined using students' *t*-tests for all variables. To address the secondary goal of this study, one-way ANCOVAs with Tukey multiple comparison post hocs were used for establishing differences between the NST, ST and Expert groups at the last trial. Levenes' tests for homogeneity of variance were used to examine the inter-subject variability between each group at post-practice given the expected reduction of variability in the expert group.

Sex (male and female) was included as the covariate in all statistical tests given that previous research has shown females demonstrated an earlier maximum flexion during the upswing (P3S) than males (Busquets, Marina, Irurtia, Ranz, and Angulo-Barroso, in press). Statistical significance was set at p<.05 level. P adjustments were conducted to control for multiple comparisons when appropriate. When normal distribution (Kolgomorov-Smirnov test) and homogeneity of variance (Levene test) were verified, parametric statistics were used; else non-parametric tests were used. Only the statistical significant results were reported. All tests were performed with Systat 11.0 (Systat Software, Inc., San José, CA, USA) and SigmaStat 3.1 (Systat Software, Inc., San José, CA, USA).

Results

Qualitative description of CRP

Qualitative assessment of the continuous relative phase was conducted by three of the authors blind to group assignment and reached a case by case agreement of 93%. This process classified novice participants and expert gymnasts in three coordinative patterns (a, b, and c) on the basis of the P2H-P2S and P3H-P3S curve shapes (see Figure 3). Disagreements were resolved by selecting the coordinative pattern with more votes. Qualitative analyses classified 7 participants in the (a) coordinative pattern, 6 in the (b), and 2 in the (c) for non-spontaneous-talented group during the pre-practice; while in the post-practice 5 participants belonged to each coordinative pattern. On the other hand, spontaneous-talented group before practice was classified as follow: 5 participants in the (a) coordinative patter, 1 in the (b), and 4 in the (c). After practice the ST group showed 1 participant in the (a), 3 in the (b), and 6 in the (c) coordinative pattern. All the expert gymnasts had a (c) type of coordination,

Non-spontaneously talented (NST) vs. spontaneously talented (ST)

The 2x2 ANCOVA for the swing amplitude revealed that there was a significant group ($F_{1,22}$=8.44, p=.008) and trial (time) ($F_{1,22}$=11.51, p=.003) main effect (Figure 4a) (see Table 1 for *M* and *SD* details). When student t-tests compared the pre- and post-practice magnitude of change no differences between the NST and ST groups were found, although differences between the novice groups decreased with practice.

The analysis of 2x2 ANCOVAs for the inter-joint reversal points yielded significant 'group by time' interaction for P1H-P1S ($F_{1,22}$=10.01, p=.005) and P2H-P2S ($F_{1,22}$=5.28, p=.032). Indeed, simple main effects showed that the ST group improved P1H-P1S and P2H-P2S from pre- to post-practice (becoming closer to reference values, in this case values of the Expert group) while the NST group worsened despite practice (Figure 4b and 4c) (see Table 1 for *M* and *SD* details), but statistical significant differences were only shown in the NST group for P1H-P1S (t = 2.693, p =.026) (Figure 4b). The students' *t*-test showed significant differences between the NST and ST groups on P1H-P1S ($F_{1,22}$=10.01, p=.005) and P2H-P2S ($F_{1,22}$=5.28, p=.032) (represented in the Figure 4b and 4c with a full circle).

The 2x2 ANCOVAs for the deviation phase (DP) variables demonstrated significant time main effect ($F_{1,22}$=6.52, p=.018) and 'group by time' interaction ($F_{1,22}$=5.12, p=.035) for DP P2h-P2S (see Table 1 for *M* and *SD* details). No significant simple main effects were yielded, but it is important to note that the ST group increased the variability of the coordination mode during the P2H-P2S and deviated more from to experts while the NST group maintained similar values of DP after practice. The students' *t*-test comparing magnitude of changes from pre- to post-practice showed significant differences between the NST and ST groups on DP P2H-P2S ($F_{1,22}$=5.02, p=.035) (represented in the Figure 4d with a full circle).

Sex as a covariate in the 2x2 ANCOVAs presented a significant interaction with the group factor only for the DP P2H-P2S ($F_{1,22}$=5.12, p=.034). The sex covariate was also significant in the students' *t*-test for the DP P2H-P2S ($F_{1,22}$=5.12, p=.034). These results were due to a decrease in variability in females while males increased from pre- to post-practice.

****Figure 3 near here****

Novices vs. Experts (3 groups)

Examining group differences at post-practice, the One-way ANCOVAs pointed out differences between expert and novice for the swing amplitude ($F_{2,30}$=118.70, p=.000), the P2H-P2S inter-joint phase ($F_{2,30}$=4.63, p=.018) and the deviation phase (DP) in P2H-P2S (Table 1). The post hoc test showed significant differences between both novice groups (ST and NST) and the experts for the swing amplitude, but there were not significant differences in paired group comparisons in P2H-P2S and DP P2H-P2S. However, inter-subject variability tests (Levenes) yielded significant differences between the expert gymnasts and novice participants for P3H-P3S, P2H-P2S absolute difference in the CRP, and P2H-P2S deviation phase in CRP indicating more consistency in the expert group than the both novice groups.

In addition to these findings, the sex covariate was significant in One-Way ANCOVA for P3H-P3S ($F_{2,30}$=4.73, p=.038) and P3H-P3S absolute differences in CRP.

In summary, these results suggest novice participants improved their performance (swing amplitude) due to practice independent of group membership. Group differences for the coordination variables mainly occurred in the downswing (-100-0%), specially in the P2H-P2S. The ST group became closer to the experts by shortening the inter-joint reversal points of the hip and shoulder in P1 and P2. In addition, the ST variability within subject increased during the P2H-P2S. Meanwhile, the NST group differed from expert values by separating the reversal points of P1H-P1S and P2H-P2S. On the other hand, the expert group showed more consistency in the P3H-P3S inter-joint reversal point and P2H-P2S absolute difference in CRP and deviation phase.

Discussion

The main aim of this study was to describe coordination changes and their variability in the acquisition of a novel task (swing on high bar) due to practice and initial talent. Both, the amount and quality of practice accumulated by individuals and also their a-priori talent may impact changes in movement coordination (Delignières et al., 1998; Teulier et al., 2007). A unique consideration included in this research was the treatment of the data clustering by the individual’s initial performance. We hypothesized larger improvements in performance, coordination and its variability for the spontaneous-talented group (ST) than the non-spontaneous-talented group (NST). The novice participants’ swing amplitudes increased as a result of a two-month practice period. Contrary to our hypothesis, performance improved to a similar extent in both groups suggesting a comparable effect of practice. Improvements after practice for oscillation amplitude in novice participants were also found by several authors in different swing skills: in parallel bars (Delignières et al., 1998), lateral swing on a suspended platform (Teulier et al., 2007), and swing on a ski apparatus (Vereijken, Van Emmerik, Bongaardt, Beek, and Newell, 1997; Teulier, Nourrit, and Delignières, 2006). These authors proposed improvements in performance due to practice in novice participants may or may not imply changes in coordination. Furthermore, they suggested modifications in coordinate mode are related to skill difficulty and amount of practice.

Although not statistically different, the NST group improved 18% of the swing amplitude compared to 11% for the ST group. These results could represent a larger gain due to practice in the NST. Regardless, it would be interesting to explore how each group accomplish this improvement (i.e. changes in coordination or not, and whether changes in coordination are similar between novice groups). Also, it will be important to observe whether changes in both groups are closer to an effective coordination mode. An effective coordination mode for the swing on the high bar was defined by the expert gymnasts’ coordination for the purpose of this paper.

One form of analyzing coordination was the qualitative description of the continuous relative phase (CRP) plots. Three coordinative patterns were defined with the (a) and (b) patterns representing a progressive change to achieve the expert (c) coordinative pattern. Indeed, all expert gymnasts of this study were classified in the (c) coordinative pattern. The expert coordinative pattern was characterized by a close P2H-P2S in relative phase which means that both arms and legs had similar actions in relation to the trunk; whereas it showed a large separation of P3H-P3S in both time and relative phase which means that hip and shoulder moved disjointly (i.e. at different points in time). Knowing the movement action by experts during the longswing, P2 is distinguished by hip and shoulder angles in relation to the trunk increasing, while the opposite occurs around P3. While the (a) coordinative pattern showed great variability of curves for the P2H-P2S and similar actions of the joints at similar time in P3 (small increase or decrease from P3H to P3S), the (b) coordinative pattern revealed that hip and shoulder actions were disjointly performed at different time in P2 and P3 (large change in both joint events). Changes due to practice from an (a) or (b) coordinative pattern to a more advanced coordinative pattern were interpreted as the discovery of a more effective coordination mode to perform the longswing. The ST group after practice decreased the number of participants in the (b) coordinative pattern, while the (c) coordinative pattern was increased to 60% of the participants. This means that the ST group modified their hip and shoulder relationships at P2 and P3 moving closer to the expert pattern. In contrast, the effect of practice in the NST group resulted in an even distribution between the three coordinative patterns. Therefore, no consistent coordinative improvements could be ascribed to this group. We would suggest that a more talented initial skill level of the participants provided an advantage to achieve a more effective coordination mode with practice. However, no significant findings were yielded analyzing the mean absolute relative phase (MARP) between contiguous events of different joints (P1H-P1S, P2H-P2S, and P3H-P3S). This lack of significance may be due to MARP being an overall estimate in addition to the large variability found among subjects.

While our performance variable (swing amplitude) did not support our hypothesis, variables of coordination (the above mentioned qualitative description of CRP, the inter-joint reversal points and deviation phase) and their variabilities yielded significant results. In fact interactions when examining the practice effects within each group were found for the P1H-P1S and P2H-P2S. These inter-joint reversal points critically differentiated the two groups. The ST group reduced the time lag between the events of hip and shoulder during the downswing (-100-0%) getting them closer to expert values. The NST group worsened the two inter-joint reversal points with these points occurring more distant from each other; despite that at the beginning of the study they showed P1H-P1S values closer to experts than the ST group, and similar P2H-P2S values to the ST group. Several studies proposed two stages in the process of learning a new task: (1) appropriate placement of task events, that is, the spatial sequences of the movement, and (2) the dynamic joint control (Gentile, 1998, in everyday functional tasks; Hung, Kaminski, Fineman, Monroe, and Gentile, 2008, in a throwing task). In these studies the early stage of learning is characterized by a relatively fast spatial sequence acquisition, while the dynamic control at the joint level improves parallel but with slower rate. Our results seem to indicate that the initial skill level could modify the practice effect on the execution of the spatial sequence of the movement since we found a group by practice effect.

In addition, the consistency of the inter-joint reversal points in each group was different. In skill acquisition consistency of the inter-subject variability could be related with the importance of the event (Koeing, Tamres, and Mann, 1994; Fleisig, Chu, Weber, and Andrews, 2009).The ST group showed less variability in P1H-P1S while the NST group remained with a large variability in all inter-joint reversal point, P1, P2 and P3. Interestingly, the expert group revealed a smaller inter-subject variability in P3H-P3S than the other two inter-joint reversal points. These results seem to indicate that the most important inter-joint reversal point to perform swing is P3H-P3S. The correct execution of the P3 events is critical from a biomechanical standpoint to maintain the angular momentum in the upswing and complete the swing movement. Due to the consistency of P3H-P3S in the expert group, we would suggest that our data indirectly supports the latter proposal and stresses the importance of the time lag between the P3 events in the angular momentum maintenance across the upswing. In contrast to the experts, the ST group demonstrated a closer execution of the two P1 events and a small inter-subject variability. We interpret these results as a potential motor strategy acquired to ensure the execution of the next movements. Interestingly, the NST group showed larger inter-subject variability and relatively distant hip and shoulder events at P1, P2, and P3 suggesting the lack of a consistent group strategy to accomplish the task. In fact, these results are in agreement with the qualitative analysis of the coordinative patterns.

Because inter-subject variability can only inform about group strategies, we examined the within subject variability calculating the deviation phase to address individual behavioral stability. We observed a significant group by practice interaction in the within variability of the inter-joint coordination mode computed by the deviation phase (DP) in the CRP. Although, increased variability at skilled level (expert gymnasts) may imply larger possibility in neuromotor strategies that is, great adaptability to contextual changes, it is accepted that large values of the DP could be related with an unstable coordination mode during the early stages of learning (Robertson, 2001; Buchanan et al., 2007). We expected to find a decrease of the variability within subject related with the improvements and the amount of practice. Contrary to our expectation, the ST group became more variable within subject for the P2H-P2S, while the NST group maintained similar DP values after practice. We suggest that successive actions of the swing task are dependent of the preceding ones. In the last session of this study, the ST group could improve P2H-P2S due to both, their almost simultaneous action of the hip and shoulder at P1 and the consistency within subject of the P1H-P1S inter-joint reversal point. In other words, P1H-P1S showed similar within subject variability concurrent with changes in the inter-joint reversal point from pre- to post-practice. However, the within subject variability for P2H-P2S increased despite the improvement of the time lag between these events. Perhaps, the performance of the ST group at P2 represents an example of the two stage learning proposal by Gentile (1998) and Hung et al. (2008).

Surprisingly, the NST group improved the swing amplitude without consistent changes in coordination variables and despite showing closer values to experts before practice for some variables.

The NST group showed values closer to expert than the ST group before practice, but only in 3 out 12 coordination variables (P1H-P1S, difP1H-P1S, and difP3H-P3S), and it is important to note that 2 of them are related to the first events (P1). On the contrary, the ST group is differentially closer to expert than NST group in also 3 out of 12 coordination variables but those are related to P2 events (MARP P2H-P2S, difP2H-P2S, and DP P2H-P2S). We interpret this as a possible advantage of the ST group at P2 (better performance), while the NST group had an initial “better” performance at P1. The consequences of a “better” initial performance at P2 means a larger swing amplitude initially (pre-practice) and also the possibility to explore solutions around this point in time (P2) resulting in further improvements at post-practice. Furthermore, we would suggest that similar values of mean in P1H-P1S could be achieved for different reasons. For example, the expert group could reduce their focus in this phase of the movement, while the NST group is “working” on finding an effective coordinative mode. This phenomenon would explain NST being closer to expert values around P1.

It is important to note that different coordination modes could be used to achieve the task by the participants. We calculated absolute differences in the CRP to reveal changes in the coordination of hip and shoulder joint actions due to practice. Unexpectedly, no differences were found between the groups for the consecutives reversal points (P1H-P1S, P2H-P2S, and P3H-P3S) due to large variability. Interestingly, the absolute differences between P2H (hip extension) and P2S (shoulder extension) for the expert group revealed smaller values and large consistency, that is, the coordination mode acquired by the gymnast was relatively maintained across P2H-P2S and across all experts. We suggested that P2H-P2S coordination mode is critical in coordinative terms to allow gymnast to prepare the P3 events performing in the adequate placement and time sequence.

Nourrit et al. (2003) and Teulier et al. (2006) suggested that novices seemed to exploit their initial behavior to reach acceptable performance levels before engaging in a true coordination change. Therefore, stability in the initial coordination with improvements in the performance variable would indicate this early stage of learning. We suggest that the NST group is an example of this process of exploiting the existing behavior resulting in improvements in swing amplitude without consistent coordination changes. Furthermore, the previous authors also suggest that when the initial behavior did not improve the task anymore, the performer needs to change the coordination mode. Changes from one stable behavior to another stable behavior are characterized by increases of variability, which is typically defined as a transition phase (Clark et al., 1993; Clark, 1995; Hamill et al., 1999). We think that the ST group is an example of a transition phase involving a change in coordination mode. Comparing the skill learning of different tasks, swing in ski simulator and in parallel bars, Teulier et al. (2006) proposed that the time rate to improve performance and coordination had been affected by the tasks’ difficulty and complexity. We would add that the initial level of skill also impacted differently the time to exploit their initial behavior and start to change coordination.

Although the true process of learning cannot be characterized, our study design let us to describe the coordination changes occurred from the initial to the last session. On the basis of the experimenters’ experience coaching gymnasts, coordination changes described in this study could be applicable to other groups and ages that are faced with a longswing as a novel task. We believe that different levels of performance (swing amplitude) and expertise will be related with specific coordination modes. However, further research is necessary to support this claim. Another factor to consider in the performance of the longswing is sex. Sex as covariate in this study was significant for P3H-P3S and P3H-P3S absolute differences. The P3H-P3S sex difference was probably due to an enlargement of this period in females compare to males. In fact, females enlarged this phase due to an earlier P3H and delayed P3S while males maintained the same values (data not shown). On the other hand, P3H-P3S absolute differences in CRP were different by sex because of a larger disassociation between the hip and shoulder actions by the females than the males. However, application of force by the gymnast on the bar is only possible while extension of the shoulder (P3S) occur near the 50% of the upswing. At pre-practice ST and NST groups performed P3S around the 31% and 35% during the upswing, and therefore neither group can apply effective force to improve the amplitude of the swing. Consequently, muscular strength (related to sex) could not be a critical factor to explain our results. Although the effect of sex as a covariate yielded relatively little results, it may be worthwhile to further examine the potential differences between males and females in the process of learning the longswing, especially when swing amplitude increases and P3S is near to 50% in the upswing. Further studies would be also necessary to assess the complete process of learning.

Conclusions

In conclusion, our findings have shown that novice participants improved swing amplitude with practice, but the coordination in the downswing was different for the ST and the NST. The ST group inter-joint phases during the downswing improved and appeared more similar to the expert group. Therefore, an initial level of skill may imply an advantage in the first stage of learning, i.e. placement of the events in the right temporal sequence in the downswing. However, and despite of the initial skill level, upswing coordination will required more focused practice. We propose to focus practice first in the placement of P2H and P2S as the first steps in the process of longswing learning, then focus on the coordination mode of the P2H-P2S, and last attempt the P3 events improvements.

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Tables

Table I. Participant characteristics, pre- and post practice swing details (*mean±sd*).

	Pre		Post		
	NST (*n* = 15)	ST (*n* =10)	NST (*n* = 15)	ST (*n* = 10)	E (*n* = 9)
Participants					
Age (years)	19.95±1.99	20.67±2.64	-	-	19.00±4.47
Height (m)	1.70±0.07	1.71±0.08	-	-	1.59±0.13
Mass (kg)	66.51±13.38	66.37±9.21	-	-	54.88±15.29
Swing Amplitude (%)	80.03±15.49	104.02±18.06	98.72±14.17	115.92±23.64	198.40±0.96
Swing Inter-joint Reversal Points [a]					
P1H-P1S	-4.37±12.12	-10.37±19.19	-15.80±18.61	-1.95±3.71	-6.45±20.15
P2H-P2S	-7.53±11.90	-7.24±15.91	-13.92±14.18	-2.44±10.05	1.09±12.77
P3H-P3S	-10.33±8.69	-10.33±17.80	-14.20±10.80	-13.14±12.67	-21.24±5.35
Mean Absolute Relative Phase					
MARP P1H-P1S	51.68±34.25	57.63±29.70	57.54±28.51	60.99±43.74	64.72±37.03
MARP P2H-P2S	28.75±25.06	19.62±15.41	23.80±16.82	26.81±22.94	13.81±7.52
MARP P3F-P3S	35.67±20.09	31.22±13.87	38.25±22.23	37.85±17.93	36.97±12.45
Absolute Differences in CRP					
difP1H-P1S	52.88±66.28	33.89±39.46	78.71±85.22	34.11±38.65	78.44±65.69
difP2H-P2S	67.12±55.61	57.57±71.59	59.84±49.44	62.29±70.77	28.93±15.86
difP3F-P3S	105.51±77.87	80.97±64.59	106.63±66.04	106.18±57.43	130.96±53.18
Deviation Phase in CRP					
DP P1H-P1S	4.53±4.24	3.52±3.25	3.21±2.55	4.15±4.51	4.90±3.64
DP P2H-P2S	6.86±4.46	4.52±1.33	5.51±3.27	8.36±4.19	4.12±1.85
DP P3H-P3S	7.48±4.25	7.35±4.84	6.86±3.39	7.73±3.12	5.88±1.82

[a] All values in percentage of swing amplitude; CRP= Continuous Relative Phase

Figure captions:

Figure 1. In the upper section, swing normalization and body position angle (θ) defined by the z axis, middle grasping hand landmark (1) and the center of mass (2). Additionally, we illustrated the initial position (Pi), final position (Pf) and swing events (P1, P2, and P3) from the hip (H) and shoulder (S) joints. For simplicity, H and S events have been represented at the same instant of time for P1-P3. In the lower section, the continuous relative phase between the hip and shoulder joints during a longswing of an expert gymnast is represented.

Figure 2. Schematic illustration of the experimental setup: (1) high bar; (2) participant hung from the high bar, and the detail of the plastic tube that covered the bar (2a) the training straps disposition (2b), and the participant's hands attached to the high bar and gripped to the plastic tube (2c). In addition, camera locations (3), and reference system (x, y and z axis) are depicted.

Figure 3. Plots of the Continuous Relative Phase (CRP) between the shoulder and the hip. Three examples from different participants representing the three observed coordinative patterns: a,b, and c. CRP patterns were qualitatively assessed observing changes in the relative angle in P2 and P3: (a) small increase or decrease from P3H to P3S; (b) large change between P2H and P2S, and large increase from P3H to P3S; and (c) small change between P2H and P2S relative angle, and large increase from P3H to P3S.

Figure 4. Results of the two (Group) x two (Time) ANCOVA with repeated measures comparing pre- and post-practice values are depicted in (a) swing amplitude, (b) P1H-P1S, (c) P2H-P2S, and (d) DP P2H-P2S. The expert group (E) means (solid line) of these variables are provided for comparison. (✱) indicates significant group or time differences. Interaction effects are not presented for simplicity. In addition, significant results of the student's t-tests comparing magnitudes of the change between pre- and post-practice for NST and ST groups are indicated with (●).

Figure 1

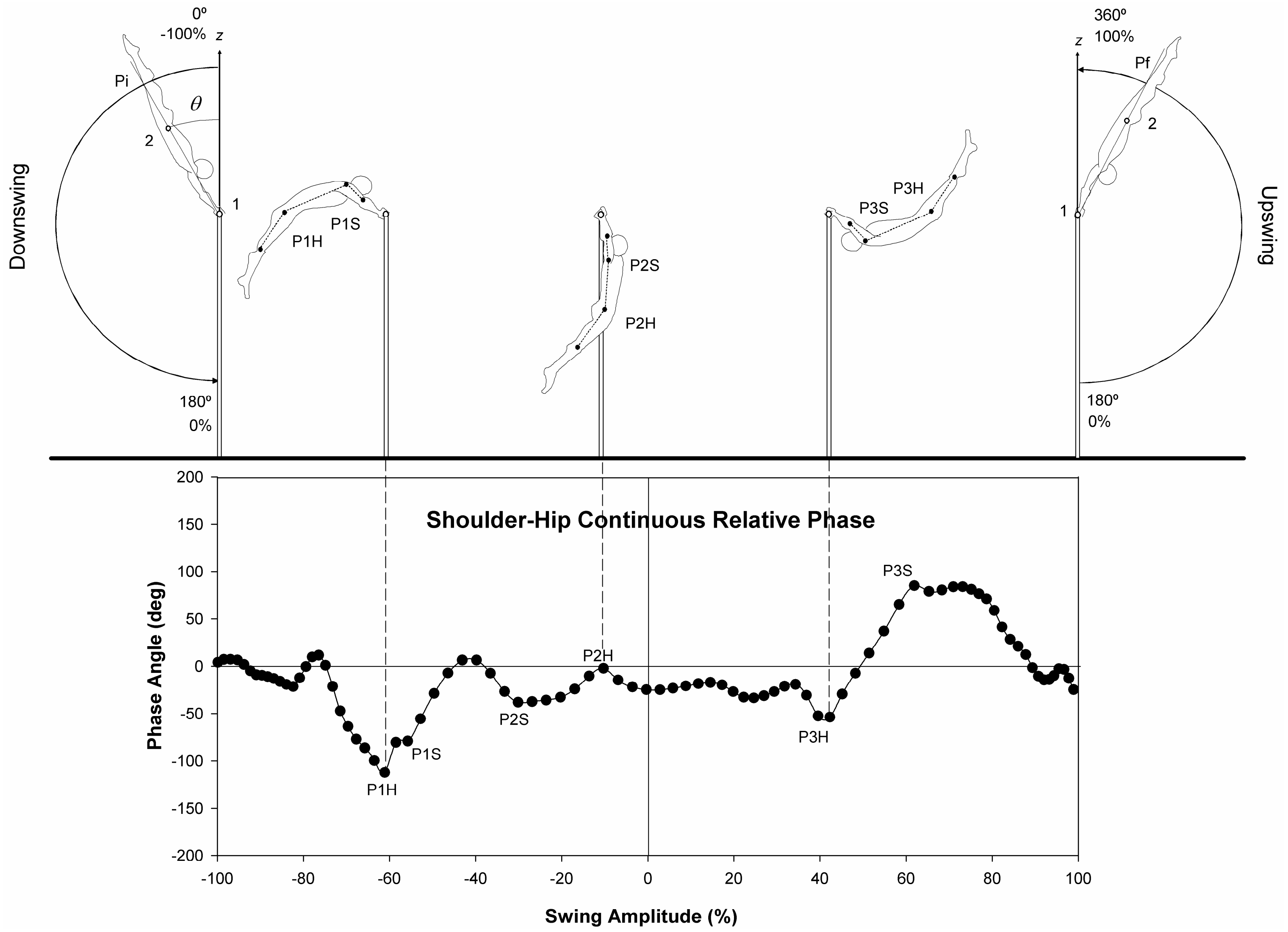

Downswing
0º
-100%
z
Pi
θ
2
1
180º
0%
P1H
P1S
P2S
P2H
P3S
P3H
360º
100%
z
Pf
2
1
180º
0%
Upswing
Shoulder-Hip Continuous Relative Phase
Phase Angle (deg)
200
150
100
50
0
-50
-100
-150
-200
P1H
P1S
P2S
P2H
P3H
P3S
-100
-80
-60
-40
-20
0
20
40
60
80
100
Swing Amplitude (%)

Figure 2

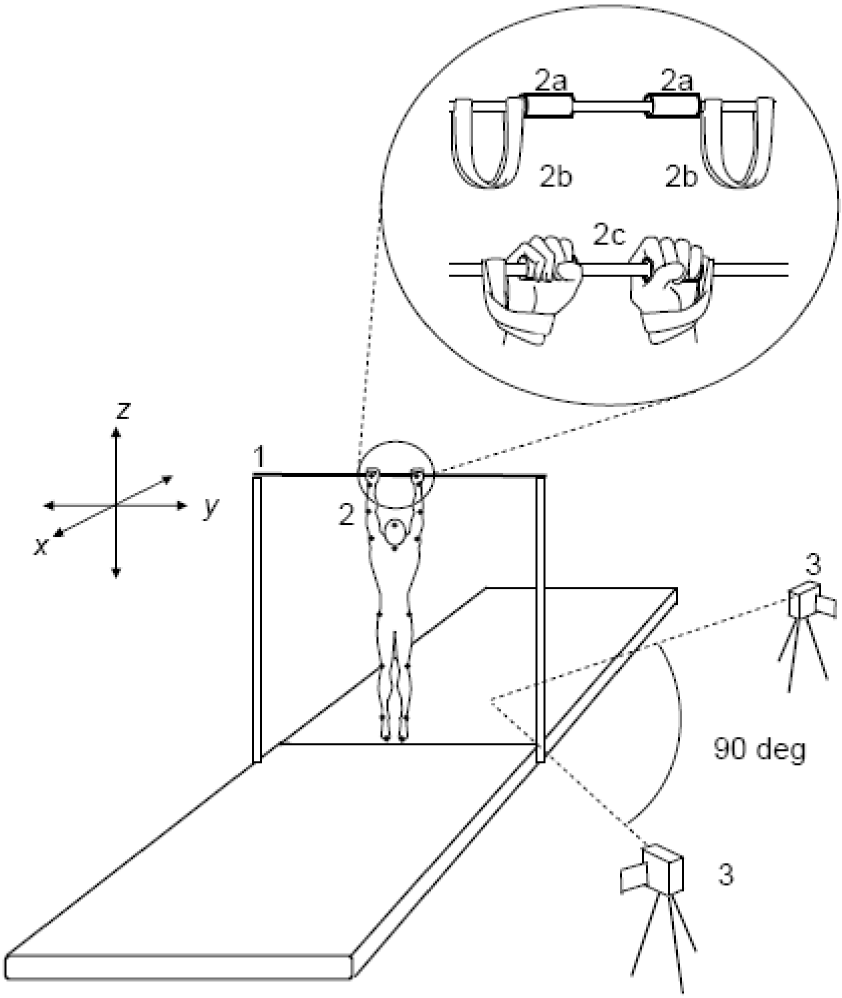


Figure 3

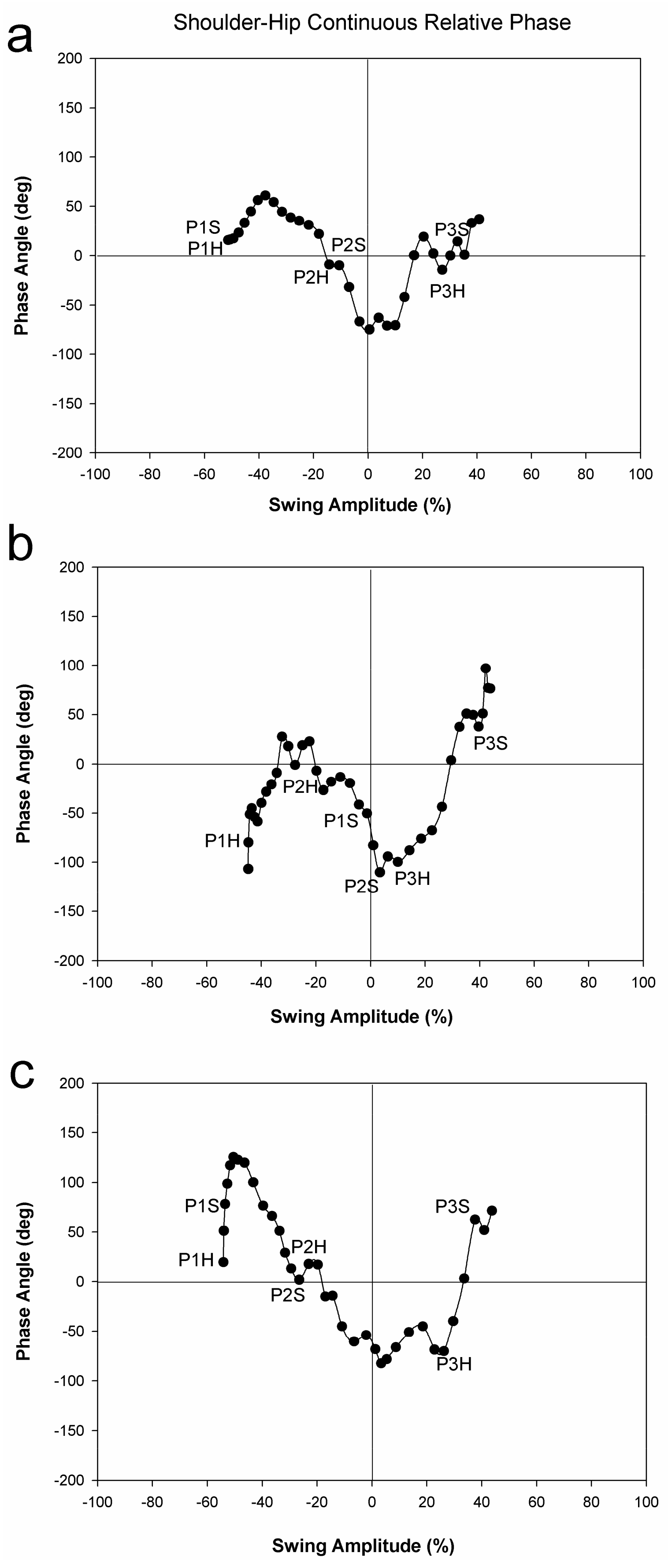
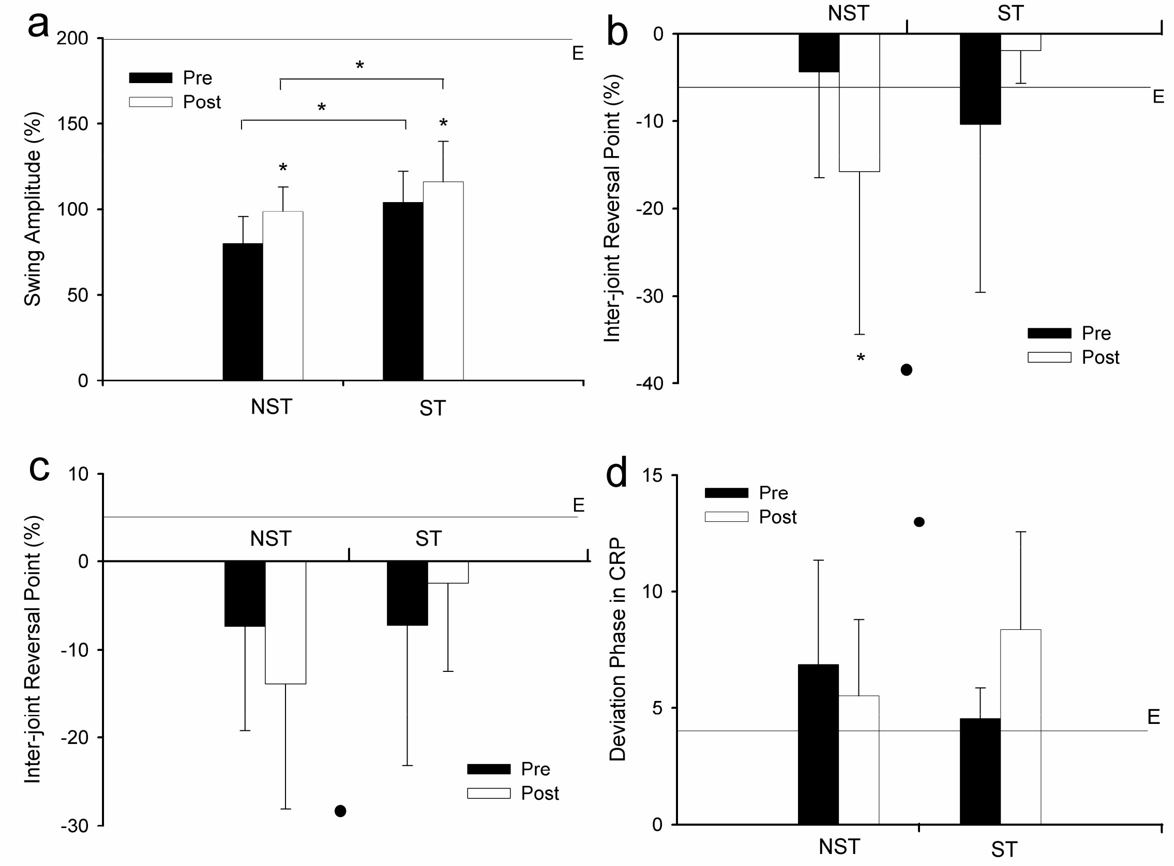

a
Shoulder-Hip Continuous Relative Phase
Phase Angle (deg)
200
150
100
50
0
-50
-100
-150
-200
Swing Amplitude (%)
-100
-80
-60
-40
-20
0
20
40
60
80
100
P1S
P1H
P2S
P2H
P3S
P3H
b
Phase Angle (deg)
Swing Amplitude (%)
P1H
P2H
P1S
P2S
P3H
P3S
c
Phase Angle (deg)
Swing Amplitude (%)
P1S
P1H
P2H
P2S
P3S
P3H

Figure 4


a
200
150
100
50
0
Swing Amplitude (%)
Pre
Post
*
*
*
*
E
NST
ST
b
0
-10
-20
-30
-40
Inter-joint Reversal Point (%)
NST
ST
E
Pre
Post
*
●
c
10
0
-10
-20
-30
Inter-joint Reversal Point (%)
E
NST
ST
Pre
Post
●
d
15
10
5
0
Deviation Phase in CRP
Pre
Post
●
E
NST
ST

Chapter 6. Skill acquisition of the swing in high bar gymnastics across age

(in preparation)

Skill acquisition of the swing in high bar gymnastics across age

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Skill acquisition of the swing in high bar gymnastics across age

Abstract

An effective motor strategy (performance and coordination) ought to be discovered during the process of skill acquisition. Coordination has been defined as the stable spatial-temporal relationship among limb segments and joints to achieve the task's goal. Discovering new modes of coordination may involve an individual undergoing a transition from one stable form of coordination to another. High within subject variability is characteristic of a system in transition. However, changes in the within subject variability were also observed when expertise increase. It was suggested that within subject variability conforms to a U-shaped graph as a function of skill progression. Sport skills represent an ideal situation to assess changes in performance, coordination, and the within subject variability in different levels of expertise. We selected the 'regular' long swing on high bar in gymnastics as the focus of this study because this skill is identified as a fundamental basic skill.

Two principal aims were pursued in this study: (1) to determine whether the competitive age groups (from beginners to elite) use different motor strategies in performance and coordination of the longswing, and (2) to assess changes in the within subject variability of the performance and coordination across the groups. Additionally, we analyzed the U-shaped fit of the within subject variability across the competition age groups.

Five competition age groups: G1 (8.92±0.85 years); G2 (11.08±0.67 years); G3 (12.88±0.50 years); G4 (14.78±0.57 years), and G5 (19.96±3.37 years) were used to classify participants (113 male gymnasts). We defined three events independently for hip (H) and shoulder (S) angle joints: the smallest angle during downswing (P1H, P1S); the largest angle after P1 (P2H, P2S); and the smaller angle during upswing (P3H, P3S). We focused our study in P2 and P3 given that functional phases of the longswing are defined by these events.

Three consecutives swings were analyzed for each participant. We described performance by the swing amplitude and the swing events, while coordination was assessed using the inter-joint reversal points and the absolute difference in the continuous relative phase between contiguous events of different joints. We also analyzed the within subject variability of the performance and coordination. The within subject variability was assessed in two different ways: inter-trial variability (standard deviation between the trials of the participants) and intra-trial variability (coordination changes within the trial described by the deviation phase).

Results of this study suggest that motor performance strategy changed across the groups, and correct spatiotemporal placements of events are acquired successively in agreement of their temporal sequence (first P2 events, second P3H and finally P3S). The beginners group (G1) presented a different coordination mode compared to the expert group (G5). The G4 group showed large increases of the within subject variability in P3 variables and intra-trial variability indicating a transition point to the expert coordination mode of G5. We suggest two different arguments to explain this transition point occurrence: (1) motor strategies adopted until G4 did not improve anymore the skill level; or (2) the increased demands of the sport to incorporate the longswing into more complex tasks.

Key words: Motor learning, Performance, Coordination, Transition phase, Variability

PsychINFO classification: 2330

1. Introduction

Skill acquisition is a dynamic and long process present throughout the entire life span (Clark, 1995). Practice is generally considered to be the single most important factor responsible for the permanent improvements in the ability to perform a motor skill (Guadagnoli & Lee, 2004; Nourrit, Deschamps, Lauriot, Caillou, & Delignieres, 2000). However, from a dynamical systems approach, the acquisition of a motor skill is conceived as an emergent property from the complex interplay between practice and a set of interrelated constraints (Clark, 2002; Handford, Davids, Bennett, & Button, 1997; Kugler, Kelso, & Turvey, 1980; Marin, Bardy, & Bootsma, 1999; Nourrit et al, 2000). These constraints have been categorized in environmental, task and organismic (Clark, 1995; Handford et al., 1997; Holt, 2005; Newell, 1986; Nourrit et al., 2000; Thelen & Smith, 1994). The organismic constraints include physical characteristics such as weight, height, and body shape, together with psychological and emotional attributes. When considering the process of skill acquisition, the specifics of the organismic constraints could be impacted by two other processes. First, the individual level of the development as a biological maturation, and second, the accumulation of expertise capabilities. As these processes advance with age, the organismic constraints will also change. For example, motor expertise's level is usually considered an organismic constraint given that the amount of particular motor skills' practice during years could change physical, perceptual, and psychological attributes from what they were before practice (Gautier, Marin, Leroy, & Thouvarecq, 2009; Marin et al., 1999). In order to consider both processes, biological development and expertise level, studies have traditionally observed learning in relation to the age of the individual performing the task (Fleisig, Barrentine, Zheng, Escamilla, & Andrews, 1999; Forssberg & Nashner, 1982; King, Kagerer, Contreras-Vidal, & Clark, 2008; Streepey & Angulo-Kinzler, 2002).

The interactions between biological development, practice, task demands, and environment have an impact not only on movement performance but also on movement coordination (Newell, 1986). According to Irwin and Kerwin (2007b), coordination has been defined as the stable spatial-temporal relationship among movement system components (i.e. limb segments and joints) to achieve the task's goal. An effective mode of coordination among the participating joints and limbs ought to be discovered during the process of skill acquisition (Bernstein, 1967; Hong & Newell, 2006; Stergiou, Jensen, Bates, Scholten, & Tzetzis, 2001; Temprado, Della-Grasta, Farrell, & Laurent, 1997). Limb segments and joints are in an in-phase coordination mode when they move in synchrony with a 0º phase lag between them, while the coordination is in an anti-phase mode when joints or segments move in opposite directions with a phase lag of 180º. However, multiple intermediate out-of-phase coordination modes exist between in- and anti-phase coordinations.

It has been proposed that two stages of learning occur in parallel but with different time rate during a motor skill acquisition (Chow, Davids, Button, & Koh, 2007; Gentile, 1998; Hikosaka, Nakamura, Sakai, & Nakahara, 2002; Hung, Kaminski, Fineman, Monroe, & Gentile, 2008; Teulier, Nourrit, & Delignières, 2006): (1) early learners attempt to establish basic relationships among motor system components to achieve functional and goal-directed movements with the appropriate placement of task events, that is, they focus on the spatial sequences of the movement; and (2) later in skilled performance, the adoption of the coordination mode which allows a better adaptation to the mechanical constraints of the task can be observed. Consequently, performers at the skilled stage of learning are able to produce movements that appear effortless and fluid (Chow et al., 2007). The early stage of learning is characterized by a relatively fast spatial sequence acquisition, while the dynamic control at the joint level improves parallel but at a slower rate.

Progress towards expertise would consist in a process of sequential elaboration and stabilization of different states of coordination (Temprado et al., 1997). Discovering new modes of coordination may involve an individual undergoing a transition from one stable form of coordination to another (Handford et al., 1997; Temprado et al., 1997). Stable forms of coordination show low variability and represent behavioral states that are reproducible and independent of each other; while high variability is characteristic of a system in transition (Clark & Phillips, 1993; Clark, 1995; Hamill, van Emmerik, Heiderscheit, & Li, 1999). Higher within subject variability of coordination in similar conditions could reveal transition phases in learning (Clark et al., 1993; Clark, 1995; Hamill et al., 1999). However, changes in the within subject variability were also observed when expertise increase. In the early stages of learning variability is high due to exploration of new modes of coordination and decreased practice (Buchanan, Zihlman, Ryu, & Wright, 2007; Robertson, 2001), but in expert performers variability can also be great to provide the flexibility to adapt movement to specific contexts (Davids, Glazier, Araújo, & Bartlett, 2003; Hamill et al, 1999; Wilson, Simpson, van Emmerik, & Hamill, 2008). It was suggested that within subject variability conforms to a U-shaped graph as a function of skill progression (Wilson et al., 2008). These difference sources of within subject variability make difficult its interpretation. In addition, within subject variability can be analyzed as the variability between trials of the same individual (inter-trial variability) or as changes in coordination mode during the execution of the trial (intra-trial variability).

Learning sport skills represent an ideal situation to assess changes in performance, coordination, and both types of within subject variability (inter- and intra-trial) in different levels of expertise. In fact, influence of the expertise level in gymnastics performance and coordination has been previously examined comparing participants of different skill level but similar age (Baudry, Seifert, & Leroy, 2008; Gautier et al., 2009; Busquets, Marina, Irurtia, Ranz, & Angulo, in press; Marin et al., 1999). We selected the ‘regular’ or ‘traditional’ backward swing on high bar (longswing) in gymnastics as the focus of this study because the coaching literature identified this skill as a fundamental basic skill (Hiley & Yeadon, 2003a; Hiley & Yeadon, 2003b; Irwin & Kerwin, 2005; Irwin & Kerwin, 2007b; Kopp & Reid, 1980; Peccolo & Blaise, 1997). The majority of movements on the high bar belong to a group of rotations in the vertical plane around a horizontal axis derived from the longswing (Brüggemann, Cheetham, Alp, & Arampatzis, 1994). The aim of the ‘regular’ backward swing is to go from handstand to handstand position through rotation around high bar with a straight body (Hiley et al., 2003b; Witten, Brown, Witten, & Wells, 1994). Full extension of arms and legs during the whole movement is required to achieve the quality standards defined by the Fédération Internationale de Gymnastique (FIG) Code of Points (2009). The importance of the hip and shoulder flexion and extension for the successful execution of the swing is well documented in several studies (Arampatzis & Bruggemann, 1999; Gervais & Tally, 1993; Hiley et al., 2003b; Kerwin, Yeadon, & Harwood, 1993; Kopp et al., 1980; Witten et al., 1994; Yeadon & Hiley, 2000). From a mechanical approach, two functional phases during the longswing have been identified: (1) hip functional phase, a rapid hyper-extension to flexion of the hip after the gymnast passes through the lowest part of the circle (Brüggemann et al., 1994; Hiley et al., 2003b; Irwin & Kerwin, 2007a; Irwin et al., 2007b; Yeadon et al., 2000), and (2) shoulder functional phase, flexion to extension of the shoulder joint before the highest point of the circle (Hiley et al., 2003b; Irwin et al., 2007a; Irwin et al., 2007b; Yeadon et al., 2000). The hip functional phase is typically executed by the gymnast in an attempt to maintain the angular momentum reducing the radius between the center of mass (CM) and the rotational axis (Yeadon et al., 2000; Irwin et al., 2005; Irwin et al., 2007a). On the other hand, gymnast performs the shoulder functional phase to continue gaining potential energy pushing up the CM over the bar. To maintain the positive balance between the angular momentum created during the downswing and the angular momentum lost in the ascending phase adequate coordination between the hip and shoulder (inter-joint coordination) is critical.

Several studies have investigated the optimal kinematics and kinetics to perform the swing in the high bar (Arampatzis et al., 1999; Gervais et al., 1993; Hiley et al., 2003b; Kerwin et al., 1993; Kopp et al., 1980; Yeadon et al., 2000; Witten et al., 1994). In addition, comparison of swing progression exercises to optimal skill performance have also been examined (Irwin et al., 2005; Irwin et al., 2007a; Irwin et al., 2007b). However, no studies have been designed to examine learning of the high bar swing (performance and coordination changes) across ages (and therefore, years of gymnastic training). The comparison of different competition age groups could help us to identify the effects of the organismic properties (development and expertise level) on performance and coordination dynamics (Gautier et al., 2009). In addition, comparing different competition age groups allows access to a longer time scale and, therefore, to observe most relevant long-term changes than a study of reduced age range (Gautier et al., 2009; Temprado et al., 1997).

Two principal aims were pursued in this study. First, the study was designed to determine whether the competitive age groups (from beginners to elite) use different motor strategies in performance and coordination to increase the swing amplitude or achieve the complete longswing (from handstand to handstand). We focused in the inter-joint coordination between the hip and the shoulder in this study due to the task characteristics. It was hypothesized that performance and coordination would become more similar to the older age group of gymnasts (experts) whit increases in expertise. In addition, we expected that ‘expert’ performance including the spatial sequences of the movement will be acquired earlier by the younger gymnasts than the ‘expert’ modes of coordination.

The second aim of the study was to assess changes in the within subject variability of the performance and coordination across the competition age groups. We hypothesize of that within subject variability of the performance and coordination will be larger for the early competition age groups than intermediate experienced groups, but within subject variability will increase again in the older group. Additionally, we analyzed the U-shaped fit of the within subject variability across the competition age groups.

2. Method

2.1 Participants

One-hundred thirteen male gymnasts of different ages took part in the study. All of them were competing in the national competition of their age group during the year of the study, and had a minimum of more than 2 years of experience in gymnastics' training. Swinging on the high bar was trained extensively for all participants. These 113 participants were classified on basis of the national competition rules into five age groups: G1 (n=26, age=8.92±0.85 years); G2 (n=30, age=11.08±0.67 years); G3 (n=17, age=12.88±0.50 years); G4 (n=18, age=14.78±0.57 years), and G5 (n=22, age=19.96±3.37 years) (Table 1). All participants were fit and injury free at the time of the study, and each gymnast or their legal tutor signed a consent form to participate. The study was approved by the local ethics committee.

TABLE 1

2.2 The task

Several authors (Arampatzis et al., 1999; Yeadon et al., 2000; Hiley et al., 2003) have defined three events of interest independently for the hip (H) and shoulder (S) angle joint movement in the sagittal plane to characterize the longswing: the minimum angle of the hip and shoulder during downswing (P1H, P1S) and upswing (P3H, P3S); and the maximum angle between P1 and P3 of the hip (P2H) and shoulder (P2S). We focused our study in P2 and P3 (Fig. 1) given that functional phases of the longswing are defined by these events (Brüggemann et al., 1994; Hiley et al., 2003b; Irwin & Kerwin, 2007a; Irwin et al., 2007b; Yeadon et al., 2000). These events are the actual reversal points where joint movements change from extension to flexion (P2) or from flexion to extension (P3). In addition, the time lags between contiguous events of different joint (P2H-P2S and P3H-P3S) were defined.

FIGURE 1

The maximum elevation of the center of mass (CM) on the downswing, initial position (Pi), and the maximum elevation on the upswing, final position (Pf) were used to infer the total path of the swing and defined as the swing amplitude (Fig. 1).

2.3 Experimental protocol

The experiment was carried out in a covered gymnasium on a regular high bar (2.60 m from top of the mat) with two landing mats (4 x 2 x 0.2 m). Training straps were used to attach the participants' hands to the bar to reduce emotional distress and increase security (Fig. 2). In addition, to avoid blisters the participants grabbed a plastic tube that recovered the bar (see Fig. 2). In order to maintain the same friction conditions between the hands and bar across the age groups all gymnasts used the training straps and plastic tubes to perform the longswings.

FIGURE 2

After warm-up directed by the responsible coach of the gymnast, practice swings on high bar were performed by the participants. Each participant then was suspended in a quiet and extended position under the bar as the starting position. Participants were asked to perform ten consecutives swings to achieve and maintain the maximum amplitude. Participants who did not perform the complete swing moved front and back while those who completed the swing moved continuously in one direction.

2.3 Data collection

Data were collected from the quiet starting position under the bar to the tenth swing. The best three consecutive swings with the largest amplitude were selected qualitatively by an expert coach and used for analysis for those participants who did not complete the swings. When participants performed all trials as complete longswings (from handstand to handstand) the first one was discharged and the following three consecutives swings were used for analysis. The participants were filmed with two digital video cameras at a height of 1.28 m (Handycam DCR-HC23E Mini DV, SONY, Japan) located on the participant's right side and front of them describing an angle of 90 degrees between their optical axes (Fig. 2). The space was calibrated using a frame of known dimensions placed under the high bar before participants' performance (absolute mean reconstruction error=1.67 cm; RMSE=0.67). This calibration partially covered the area of interest, but a larger frame covering the space above and under the bar presented logistic problems in the selected venue. To assess the error embedded in a partial calibration, a different venue was utilized to analyze the swing movement in three expert gymnasts using both calibration frames. The new calibration frame was twice as tall (2 x 2 x 4.65 m) as the frame used in this study. When both calibrations were used and the longswing movement analyses were compared, the global average error across the entire movement was RMSE=2.8 cm, NRMSE=2.85%. Given the relatively low global average error (Angulo & Dapena, 1992; Hinrichs & McLean, 1995) and the logistic problems we deemed adequate the use of the "small" frame in this study. A reference system was defined with the y axis as the high bar, the vertical axis as the z, and the axis perpendicular to this plane as the x (Fig 2).

2.4 Data reduction

The videotaped images captured at a sample rate of 50 Hz were manually digitized by the first author with Kwon3D 3.00.033 (Young-Hoo Kwon & Visol, Inc). The intra-coder reliability for the whole trajectory achieved an average value of RMSE=2.3 cm when the longswing of the participants were analyzed. An 18 landmarks body model was utilized with markers located on the middle of the grasping hand, wrist, elbow, shoulder, great trochanter, femoral condyle, lateral malleolus and tip of the foot bilaterally, and vertex and sternum. Raw data were smoothed using Butterworth Low-pass fourth order recursive filter (Winter, 1990). Cut-off frequency was set at 5 Hz based on a residual analysis and qualitative evaluation of the data (Giakas, Baltzopoulos and Barlett, 1997; Winter, 1990). The flexion – extension angle and angular velocities for the hip and shoulder in the sagittal plane were computed. Angular movements at the hip were derived from the angle between the right thigh and trunk (shoulder, great trochanter and femoral condyle markers) and movements at the shoulder from the angle between the right upper arm and trunk (elbow, shoulder and great trochanter markers). In addition, a custom software developed in Matlab version 7.01 (Mathworks R14) identified peaks and valleys in the joint angle displacement-time traces.

Body position angle was defined as the angle formed by the line connecting the CM with the middle of the grasping hand and the vertical (*z*-axis) of the coordinate system (Yeadon et al., 2000) (Fig. 1a). We calculated the location of the center of mass differently on basis of the gymnast age. Jensen’s equations for subjects between 4 and 20 years (Jensen, 1989; Jensen & Nassas, 1988) were used to compute CM on gymnasts younger than 20 years, while De Leva’s data (De Leva, 1996) were applied to calculate CM of 20 years or older gymnasts.

2.5 Variables

Three consecutives swings were analyzed for each participant. The motor strategies adopted for each participant were characterized by the performance and coordination variables. We described performance by the swing amplitude and the swing events, while inter-joint coordination was assessed using the inter-joint reversal points and the absolute difference in the continuous relative phase between contiguous events of different joints. On the other hand, we analyzed the within subject variability of the performance and coordination. The within subject variability was assessed in two different ways: inter-trial variability (between the trials of the participants) and intra-trial variability (coordination changes within the trial). We described the inter-trial variability using the standard deviation of the three trials for each participant in the performance and coordination variables, and the intra-trial variability computing the deviation phase in each swing performed by the participants.

The main index of performance was the amplitude of the pendular oscillations of the body position (swing amplitude). Swing amplitude was defined in a reference where the 0 degrees of body position angle defined as -100% and the 180 degrees of body position defined as 0% and the 360 degrees of body position defined as 100% (Fig. 1a). The minimum percentage of the path, maximum elevation of the CM on the downswing, and the maximum percentage of the path, maximum elevation of the CM on the upswing, of each trial defined the start (Pi) and end points (Pf), respectively. The total path between Pi and Pf was the swing amplitude.

Another relevant index of performance was the placement of the critical events. Focusing in the critical events of the swing functional phases, we analyzed the hip and shoulder angle joint movements during the swing to identify these events (P2H, P3H, P2S and P3S), that is reversal points of both joints (Fig. 1). The hip and shoulders events were expressed in swing's percentage.

In order to characterize the coordination between the hip and shoulder in the swing in high bar, we defined inter-joint reversal points (P2H-P2S, and P3H-P3S), also as percent of swing amplitude, using the critical events for both angle joint movements of the hip and the shoulder (Fig. 1). These inter-joint reversal points indicate the temporality of the hip and shoulder actions and therefore it is a measurement of temporal coordination.

Coordination was also assessed with the continuous relative phase (CRP). The CRP was used to represent the phasing relationships or coordination mode between the actions of the two joints at every point. Previous to calculate CRP, the angular displacement (θ) and angular velocity (ω) of each swing were normalized according to Hamill et al. (1999), and then the phase angles using $\varphi=\tan^{-1}(\omega / \theta)$ were computed. In addition, the calculated phase angles were corrected so the values range was between 0-180º. Finally, each CRP was obtained by subtracting the phase angle of the distal joint (hip) from that of the proximal (shoulder), namely $\varphi_{\text{shoulder-hip}}$ (Clark et al., 1993; Hamill et al., 1999; Irwin et al., 2007b).

In Figure 1, the continuous relative phase graph of an expert gymnast was depicted for a longswing in high bar. Regarding the phase angle (ordinate axis), its value around -20% indicated an in-phase relationship between the hip and shoulder. From -3% (when the shoulder achieved the maximum extension, P2S) coordination changed slower to an out-of-phase mode mainly due to hip's extension while the shoulder maintained the same angle. Around 40% of the upswing (when the hip achieved the maximum extension, P3H) the coordination changed faster to an out-of phase mode (mainly due to the time delay between hip's and shoulder's flexions). Regarding the % swing amplitude (abscissa axis), during the inter-joint reversal points P2H-P2S and P3H-P3S events were performed relatively far apart.

The effect of the hip and shoulder joint actions (extension or flexion) at each reversal point (P2 or P3) on the coordination mode were assessed by the absolute differences in the continuous relative phase. We computed the absolute differences in the CRP by subtracting the relative phase value of the hip and shoulder events (for P2 difP2H-P2S=|φP2H- φP2S|, and for P3 difP3H-P3S=|φP3H- φP3S|). A large value of the absolute difference indicated that the consecutive actions of the two joints had a great effect on coordination mode. This would be expected to occur at P3H-P3S. In contrast, the expected actions of hip and shoulder at P2 would produce a smaller change in coordination. That is, a smaller absolute difference of the computed CRP than in P3.

We analyzed the within subject variability between trials (inter-trial variability) computing the standard deviation of the performance (SD swing amplitude, SD P2H, SD P3H, SD P2S, and SD P3S) and coordination variables (SD P2H-P2S, SD P3H-P3S, SD difP2H-P2S, and SD difP3HP3S) for each participant. In addition, we analysed within subject variability of the coordination mode in each swing (intra-trial variability) with the deviation phase (DP) (Stergiou et al., 2001). The deviation phase was the ratio between the standard deviation of the CRP values and the number of points (data) for the analyzed section of the movement. We calculated DP in the CRP sections delimited by contiguous events of different joints (P2H-P2S or P3H-P3S) to analyze inter-joint coordination intra-trial variability during the swing. Values of the DP can be related with the consistency of the relationship between the hip and shoulder actions. A small DP value indicates more consistency in the coordination mode resulting from the consecutive action of the two joints. On the contrary, large values are typical in the early stages of learning in novice participants (Buchanan et al., 2007; Robertson, 2001).

2.6 Statistical analyses

We analyzed three consecutives swings for each participant. Differences between the three swings in each group were assessed with One-way ANOVAs with repeated measures in each variable, no significant results were found allowing us to calculate the individual mean for each performance and coordinative variable from the three selected swings. To assess the first aim of the study, that is changes in the motor strategies (performance and coordination) across the competition age groups, we used One-way ANOVAs in which the competition age group was the factor. Planned comparisons between groups were applied.

The second aim of this study was to assess changes in the within subject variability of the performance and coordination across the competition age groups. Within subject variability was analyzed differently for the inter- and intra-trial variability. To assess within subject variability of the participants performing different swings (inter-trial variability) we calculated the individual standard deviation from the selected three consecutives swings. One-way ANOVAs were used to examine changes of individual standard deviations across the competition age groups. Planned comparisons between groups were conducted. On the other hand, changes of the coordination mode within each swing (intra-trial variability) were assessed by the deviation phase in P2 and P3. We used the values of selected three swings to check intra-trial variability differences across the competition age groups applying One-way ANOVAs test. Planned comparisons were used between groups.

In addition, the U-shaped fit of the within subject variability (inter- and intra-trial) across the competition age groups was analyzed. Individual standard deviation provided values for group means of the inter-trial variability, while group means of the intra-trial variability were computed from deviation phase values. Group means of the inter- and intra-trial variability were depicted, quadratic curve were fit, and R^2 reported.

Statistical significance was set at $p<.05$ level; however, p values between .05 and .10 were also discussed. P adjustments were conducted to control for multiple comparisons when appropriate. When normal distribution (Kolgomorov-Smirnov test) and homogeneity of variance (Levene test) were verified, parametric statistics were used; else non-parametric tests were used. All tests were performed with Systat 11.0 (Systat Software, Inc., San José, CA, USA) and SigmaStat 3.1 (Systat Software, Inc., San José, CA, USA).

3. Results

3.1 Performance and coordination across competition age groups

One-way ANOVAs for the performance variables (swing amplitude and swing events: P2H, P3H, P2S, and P3S) revealed that there were significant group differences for all these five variables (Table 1). For the swing amplitude G1 showed a significant smaller value than the G3, G4, and G5 groups, while the G2 did not differ of the other groups. In relation to the swing events, simple main effects showed that younger group (G1) performed P2H, P3H, and P3S earlier than the older groups (G4 and G5). The G2 group showed an earlier execution than older groups only in the P3 events; hip flexion (P3H) was performed earlier than G4 and G5, and shoulder flexion (P3S) earlier than G5 (t=4.204, p=.000). In contrast, P2H was executed closer to the G4 and G5 values. The intermediate age group (G3) did not present differences with other groups except for the P3S (t=3.824, p=.001) that was performed closer to G4 and G5 values. Performance of the G4 and G5 was similar, but the extension of the shoulder (P2S) was executed earlier by the oldest group (G5).

The analysis of One-way ANOVAs for the coordination variables yielded significant group differences only in the P3H-P3S inter-joint reversal point (Table 1). Indeed, the simple main effects showed a larger P3H-P3S for the oldest group (G5) than the youngest group (G1). However, it is interesting to notice that P2H-P2S inter-joint reversal point showed a trend to be different across the competition age groups.

3.2 Within subject variability across competition age groups

Inter-trial variability comparisons

Examining the inter-trial variability comparing the individual standard deviation of the competition age groups, the One-way ANOVA showed significant differences in the swing amplitude variability and the SD P3H-P3S (Table 2). Simple main effects were found in the swing amplitude variability showing that the youngest group (G1) had more variability than intermediate and older groups (G3, G4, and G5). In contrast, SD P3H-P3S did not yield simple main effects between groups, but it's important to notice that G2 and G3 had more consistency than the other groups.

TABLE 2

Intra-trial variability comparisons

One-way ANOVAs for the intra-trial variability variables (DP P2H-P2S and DP P3H-P3S) did not found significant differences between the competition age groups, but it is important to note that both variables showed a tendency to differ between groups (Table 2). Deviation phase in P2 was larger for the G4 and smaller for the G5, while deviation phase in the P3 was higher for the G4 and G5.

3.3 U-shape of the within subject variability

Inter-trial variability U-shape

Group means of the inter-trial variability variables were depicted across the competition age groups and fitted with a quadratic polynomial curve to check the U-shape (Fig 3a-d, and f-i). Despite no significant differences were found between groups, inter-trial variability plots of performance and coordination in P2 (Fig. 3a-d) fit better to U-shape than the P3 ones (Fig. 3f-i), especially for the SD P2H and the SD difP2H-P2S (Fig. 3a and 3d respectively). The higher values of variability in G1 and G2 (younger groups) decrease to smaller values in G3 (intermediate group), and then increase again their values for the G4 and G5 (older groups). Focusing in the P3 performance and coordination intra-trial variability, the hip event on P3 variability decreased from the G1 to G2 and remained in similar values across the other competition age groups (see Fig. 3f). In contrast, the SD P3S (Fig 3g), SD P3H-P3S (Fig. 3h), and SD difP3H-P3S (Fig. 3i) inter-trial variability plots showed different profile. We found large values of variability in G1 that decrease to smaller values in G2 and G3. From G3 to G4 variability increase to higher values, and then decrease again for the G5 group.

Intra-trial variability U-shape

Plots of the intra-trial variability across the competition ages used group means of the deviation phase in P2H-P2S (Fig. 3e) and P3H-P3S (Fig. 3j). The intra-trial variability plots in P2 and P3 did not fit in a U-shape. Deviation phase in P2H-P2S plot remained in similar values of variability from G1 to G3 while G4 increased variability to highest values, and then in G5 variability decreased (Fig. 3e). Similar profile was observed in DP P3H-P3S, but intra-trial variability in G5 maintain the same values of the G4 (Fig. 3j). It’s important to notice that profiles of the DP group means plots were more similar to SD P3S, SD P3H-P3S, and SD difP3H-P3S plot profiles than U-shape profile.

Overall, these results suggest that ‘expert’ performance (G5) was already shown in G4, but changes in performance occurred progressively across the competition age groups. From G1 group to G2 group events of the P2 were improved (closer to the G5 values) while P3 events were improved from the G2 to G3. However, the coordination variables did not change significantly across groups, except for the P3H-P3S showing differences between the oldest group (G5) and G1. When within subject variability was analyzed, higher inter-trial consistencies were found in the swing amplitude for the G3, G4, and G5 compared to G1, and in the SD P3H-P3S for the G2 and G3 compared to the other groups. In addition, group means of the inter-trial variability in P2 variables had a better U-shape fit than in P3 variables. On the other hand, plots of the group means of the intra-trial variability showed a distinct increase in variability for G4. The same phenomenon was also observed for inter-trial variability in P3 variables.

4. Discussion

The first aim of this study was to analyze the motor strategies (performance and coordination) to increase the swing amplitude or achieve the complete longswing (from handstand to handstand) across the competition age groups. Age could impact in the organismic constraints during skill acquisition due to the individual's development and amount of expertise level (Fleisig et al, 1999; Forssberg et al., 1982; Gautier et al., 2009; King et al., 2008; Marin et al., 1999; Streepey et al., 2002). In order to observe performance and coordination long-term changes across age groups, we compared gymnasts of different competition age groups from beginners to elite. We hypothesized that performance and coordination would become more similar to the oldest age group of gymnasts (experts) as competitive age increased. Gymnast performance improved across age groups and became similar to 'expert' performance, especially for G3 and G4 groups. Contrary to our hypothesis, coordination across the groups did not show marked changes towards the 'expert' values.

Improvements in the global performance across ages were found in different tasks (in walk, Adolph, Vereijken, & Shrout, 2003; in cyclical pointing, Bourgeois & Hay, 2003; in baseball pitching, Fleisig et al., 1999). It was suggested that the improvements from beginners to experts was related with the amount of practice across years (Adolph et al., 2003). Results not presented in this study showed that age of participants correlated with the amount of practice (i.e. years training gymnastics). However, changes in performance can not be explained by practice as a single factor. Several studies suggested other critical factors impact the learning process, for example a priori talent (Busquets et al., in press; Delignières, et al., 1998; Teulier & Delignières, 2007) or skill level (Gautier et al., 2009; Marin et al., 1999; Nourrit et al., 2000).

Performance was also examined in this study by the spatial sequence of the events. All events analyzed (P2H, P3H, P2S, and P3S) showed differences across the competition age. P2 events became progressively closer to the vertical axis (0% swing amplitude) from G1 to G4, while G5 performed these events earlier in relation to vertical. However, P3H and P3S were performed progressively later across the competition age groups acquiring values of the ‘expert’ group (G5) in G4. From a biomechanical standpoint, the P3H and P3S execution are critical to maintain the angular momentum in the upswing and complete the swing movement. Small values of the P3H and P3S standard deviations of the G4 and G5 groups evidenced the relevance of these events to high level performance.

Interestingly, changes of the P2 events were observed in younger competition age groups than P3 events. The G2 group performed P2H later as % swing amplitude than the G1 group but closer to G5. In contrast P3H and P3S were executed at similar % swing amplitude to G5 by only the older age groups, G3 and G4. It’s important to notice that largest value of the group consistency performing these events also occurred at different age groups. The largest consistency for P2H, P3H, and P3S were achieved by the G3, G4, and G5 respectively. In contrast, relatively large P2S values of the standard deviation including the increased value in the expert group (G5) could be interpreted as a wide range of options to perform this event during the swing on high bar. Similar results were found by Busquets et al. (in press) comparing talented novices and non-talented novices learning swing in high bar. These authors suggested that the correct placement of critical events is learned successively in agreement with their spatio-temporal performance sequence. Our results support the above findings and suggest that motor performance strategy (spatio-temporal sequence of the events) changed across the competition age groups. Therefore, P2 events are acquired at younger age groups than P3 events, and hip flexion (P3H) is learned before the shoulder flexion (P3S) on the basis of group consistencies.

It would be expected to find some changes in coordination that could help explain the modifications found at the level of performance. We analyzed coordination by the inter-joint reversal points between contiguous events of different joints (P2H-P2S and P3H-P3S) and the absolute differences in the CRP between the same events (difP2H-P2S and difP3H-P3S). These coordination variables only yielded significant results for the P3H-P3S and a tendency for the P2H-P2S suggesting coordination differences between the beginners group (G1) and the expert group (G5). Lack of findings amongst other groups may be due to the fact that inter-joint reversal points and the absolute differences in CRP are relatively gross variables to characterize the fine tuning process in skill acquisition. In addition, the great variability in the groups make difficult to find significant differences perhaps because age may not be the best factor to group individuals.

While group variability may be informative, a better variability measure may be within subject variability. In fact, coordination transition phases in learning could be revealed by examining within subject variability (Clark et al., 1993; Clark, 1995; Hamill et al., 1999). The second aim of this study was to assess changes in the within subject variability of the performance and coordination across the competition age groups. We hypothesize that within subject variability of the performance and coordination will be larger for the early competition age groups than intermediate groups, but will increase again in the oldest group. Within subject variability was significantly different for the SD P3H-P3S, and showed a tendency for the DP P2H-P2S and DP P3H-P3S. Interestingly, G4 showed great increases of the within subject variability in these variables. We would suggest that G4 represented a transition point in the process to achieve the expert coordination mode of G5.

Additionally, we analyze the U-shaped fit of the within subject variability (both inter- and intra-trial) across the competition age groups. Two distinct patterns were observed: a U-shaped fit, and a large deviation for G4. A better U-shaped fit was found in graphs obtained from the P2 *inter-trial variability* variables supporting the results yielded by Wilson et al. (2009). Variability in the beginner group could be the effect of motor strategy (performance and coordination) exploration (Nourrit, Delignieres, Caillou, Deschamps & Lauriot, 2003; Teulier et al., 2006). Intermediate groups toward expertise (G2, G3, and G4) may have decreased variability due to exploiting their currently adopted motor strategy to improve the performance level. Finally, large flexibility and adaptability of the motor strategies adopted by the expert gymnasts (G5) resulted in increased variability for these variables. In contrast, large G4 deviations were found in graphs of the *inter-trial variability* for the P3 variables (SD P3S, SD P3H-P3S, and SD difP3H-P3S concretely) and in the intra-trial variability variables (DP P2H-P2S and DP P3H-P3S).In agreement with these results, three of the above variables (SD P3H-P3S, DP P2H-P2S and DP P3H-P3S) also showed a tendency for G4 to have increased variability suggesting again a transition point. These results could be interpreted on the basis of previous research (Nourrit et al., 2003; Teulier et al., 2006) suggesting that when initial behavior did no longer improve the task, the performer needs to change motor strategies. However, the swing amplitude between G4 and G5 were not statistically different. Therefore we propose an alternative explanation. The transition phase in G4 could be due to increased demands of the sport. Learning of the flight elements and dismounts start typically at G4. With time, expert gymnasts (G5) adapt the regular longswing (task assessed in this study) to achieve correct execution of more difficult and complex tasks (flight elements, dismounts) (Arampatzis et al., 1999; Brügemann, et al., 1994; Hiley et al., 2003a; Hiley et al., 2003b). The process of adapting and practicing the longswing facing higher demands (longswing as preparatory element for other gymnastic tasks) could create the transition phase in G4 with subsequent impact in their motor strategies to perform regular longswings.

It would be expected that *performance* variability could be affected by the transition phase found in G4. However, swing amplitude variability was significantly decreased for the G3, G4 and G5 compared to G1 and no significant differences were found in the within subject variability of the events across age groups. Clearly, the transition point in the G4 did not impact the performance variability. We would suggest that main concern of all age group gymnasts was to maintain the global performance level (swing amplitude) and therefore demonstrate more consistent performance than coordination.

When comparing performance and coordination, our expectation was that 'expert' performance including the spatial sequences of the movement (events) will be acquired earlier by the younger gymnasts than the 'expert' modes of coordination. Indeed our results support this statement and are in agreement with the previous results by Chow et al. (2007), Gentile (1998), Hikosaka et al. (2002), Hung et al. (2008), and Teulier et al. (2006). Performance variables were similar to 'expert' values (G5) in G4. Conversely, coordination mode of the 'experts' only was different to that of the beginners (G1). While lack of significant results in the coordinative variables do not address the fine tuning coordinative process, within subject variability (statistically and graphically) showed a transition point in G4. We suggest that after this transition point the 'expert' coordination mode can be adopted.

Analysis of the swing in high bar across the competition age groups allows us to describe skill acquisition in two different stages (spatial sequence earlier than coordination mode), but in different time rate depending of the event occurrence (first, extension of the hip and shoulder, second flexion of the hip, and finally the shoulder's flexion). This was especially evident by the performance variables rather than the coordination variables. Variables of coordination in this study may have reduced sensitivity to detect changes. Future research using more sensitive variables of coordination is necessary to analyze the tuning process during skill acquisition. On the other hand, graphs of the group means of the within subject variability showed qualitatively an interesting transition point, but no significant results in the variability were found. Lack of significance could stem from use of linear statistics. In fact, learning is not a linear process, and for this reason several authors propose non-linear statistics to analyze variability (Harbourne & Stergiou, 2009; van Emmerik, Rosentein, McDermott, & Hamill, 2004). Furthermore, given that performance and coordination could be impacted by skill level, future studies should examine skill level and age together as factors of analysis.

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Tables

Table 1. Participant characteristics, group means (M) and standard deviations (SD) of the performance and coordination variables, and results of One-Way ANOVA with age groups (G1-G5) as the between factor.

	G1 (*n*=26)		G2 (*n*=30)		G3 (*n*=17)		G4 (*n*=18)		G5 (*n*=22)		ANOVA	
	M	SD	M	SD	M	SD	M	SD	M	SD	p	Post-hocs
Participants												
Age (years)	8.92	0.85	11.08	0.67	12.88	0.5	14.78	0.57	19.96	3.37	-	-
Height (m)	1.31	0.05	1.39	0.07	1.48	0.08	1.62	0.10	1.65	0.05	-	-
Mass (kg)	28.62	3.42	34.3	4.87	40.29	4.91	53.63	10.80	63.36	4.97	-	-
Performance												
Swing Amplitude (%) [a]	132.00	40.29	149.78	44.90	179.07	37.57	198.73	0.33	198.75	0.27	**.001**	G1 < G3, G4, G5
Swing Events (%)												
P2H [a]	-16.67	8.87	-10.49	7.58	-9.24	5.35	-4.38	8.21	-9.46	7.08	**.001**	G1 < G2, G4, G5
P3H [a]	30.62	8.93	32.74	7.71	37.83	6.87	41.02	3.54	40.90	5.22	**.001**	G1, G2 < G4, G5
P2S [a]	-11.11	12.50	-9.22	13.02	-6.10	12.19	-1.96	11.92	-15.43	17.30	**.001**	G4 > G5
P3S	47.49	9.46	51.52	11.02	58.18	11.39	58.77	8.90	62.92	6.25	**.000**	G1 < G3, G4, G5; G2 < G5
Coordination												
Inter-joint Reversal Points (%)												
P2H-P2S [a]	-5.56	11.67	-1.28	16.35	-3.14	13.14	-2.42	10.04	5.96	15.60	**.071**	-
P3H-P3S [a]	-16.87	5.14	-18.82	4.78	-20.35	10.54	-17.76	7.93	-22.01	5.84	**.020**	G1 > G5
Absolut Differences in CRP												
difP2H-P2S [a]	54.46	24.47	57.96	33.98	49.28	16.93	51.31	29.10	50.49	28.74	.820	-
difP3H-P3S	120.80	51.65	125.06	47.89	131.62	44.62	115.26	38.19	122.75	32.61	.857	-

[a] Normality test failed. Kruskal-Wallis One-Way ANOVA on Ranks with Dunn's Method multiple comparison post hoc was performed.

Table 2. Within subject variability (inter- and intra-trial) group means (M) and standard deviation (SD) of the performance and coordination variables, and results of One-Way ANOVA with age groups (G1-G5) as the between factor.

	G1 (*n*=26)		G2 (*n*=30)		G3 (*n*=17)		G4 (*n*=18)		G5 (*n*=22)		ANOVA	
	M	SD	M	SD	M	SD	M	SD	M	SD	p	Post-hocs
Performance Inter-trial Variability												
SD Swing Amplitude (%) [a]	2.85	2.98	2.73	3.30	1.41	1.93	0.52	0.37	0.52	0.28	**.001**	G1 > G3, G4, G5
Swing Events Variability (%)												
SD P2H	4.64	3.80	3.84	2.94	3.15	1.92	3.55	3.05	5.47	3.63	.144	-
SD P3H	3.23	2.47	2.17	2.06	2.29	1.89	2.37	1.94	2.44	1.87	.489	-
SD P2S	8.85	9.26	9.03	8.98	6.41	6.84	7.63	7.48	7.84	8.57	.714	-
SD P3S [a]	4.50	4.50	3.37	2.55	2.34	2.10	5.31	4.67	4.62	4.23	.162	-
Coordination Inter-trial Variability												
Inter-joint Reversal Points Variability (%)												
SD P2H-P2S [a]	9.58	6.95	10.71	8.78	7.50	8.38	7.81	6.81	9.40	6.62	.328	-
SD P3H-P3S [a]	5.10	4.22	2.92	2.49	2.94	2.28	5.80	4.78	4.45	4.31	**.050**	-
Absolut Differences in CRP Variability												
SD difP2H-P2S [a]	30.08	22.27	24.47	18.52	18.02	10.10	21.09	13.97	21.68	12.69	.517	-
SD difP3H-P3S [a]	27.23	21.36	20.17	13.33	20.59	12.99	30.26	23.44	16.75	13.96	.126	-
Coordination Intra-trial Variability												
Deviation Phase in CRP												
DP P2H-P2S [a]	4.45	2.70	4.38	2.91	4.56	2.15	5.25	3.75	3.66	2.52	**.055**	-
DP P3H-P3S	4.97	2.93	4.92	2.06	4.94	1.53	5.67	1.81	5.54	1.89	**.074**	-

[a] Normality test failed. Kruskal-Wallis One-Way ANOVA on Ranks with Dunn's Method multiple comparison post hoc was performed.

Figure Captions

Figure 1. In the upper section, swing amplitude defined in reference of the body position angle (θ) delimited by the z axis, middle grasping hand landmark (1) and the center of mass (2). Additionally, we illustrated the initial position (Pi), final position (Pf) and swing events (P1, P2, and P3) from the hip (H) and shoulder (S) joints. For simplicity, H and S events have been represented at the same instant of time for P1-P3. In the lower section, the continuous relative phase between the hip and shoulder joints during a longswing of an expert gymnast (G5) is represented.

Figure 2. Schematic illustration of the experimental setup: (1) high bar; (2) participant hung from the high bar, and the detail of the plastic tube that covered the bar (2a) the training straps disposition (2b), and the participant's hands attached to the high bar and gripped to the plastic tube (2c). In addition, camera locations (3), and reference system (x, y and z axis) are depicted.

Figuer 3. Graphs illustrated group means of the inter-trial variability of performance (a, b, f, and g) and coordination (c, d, h, and i), and intra-trial variability of coordination (e and j). We depicted P2 variables in the upper section and P3 variables in the lower section. We also included quadratic curve fit in data points and R^2.

Figures

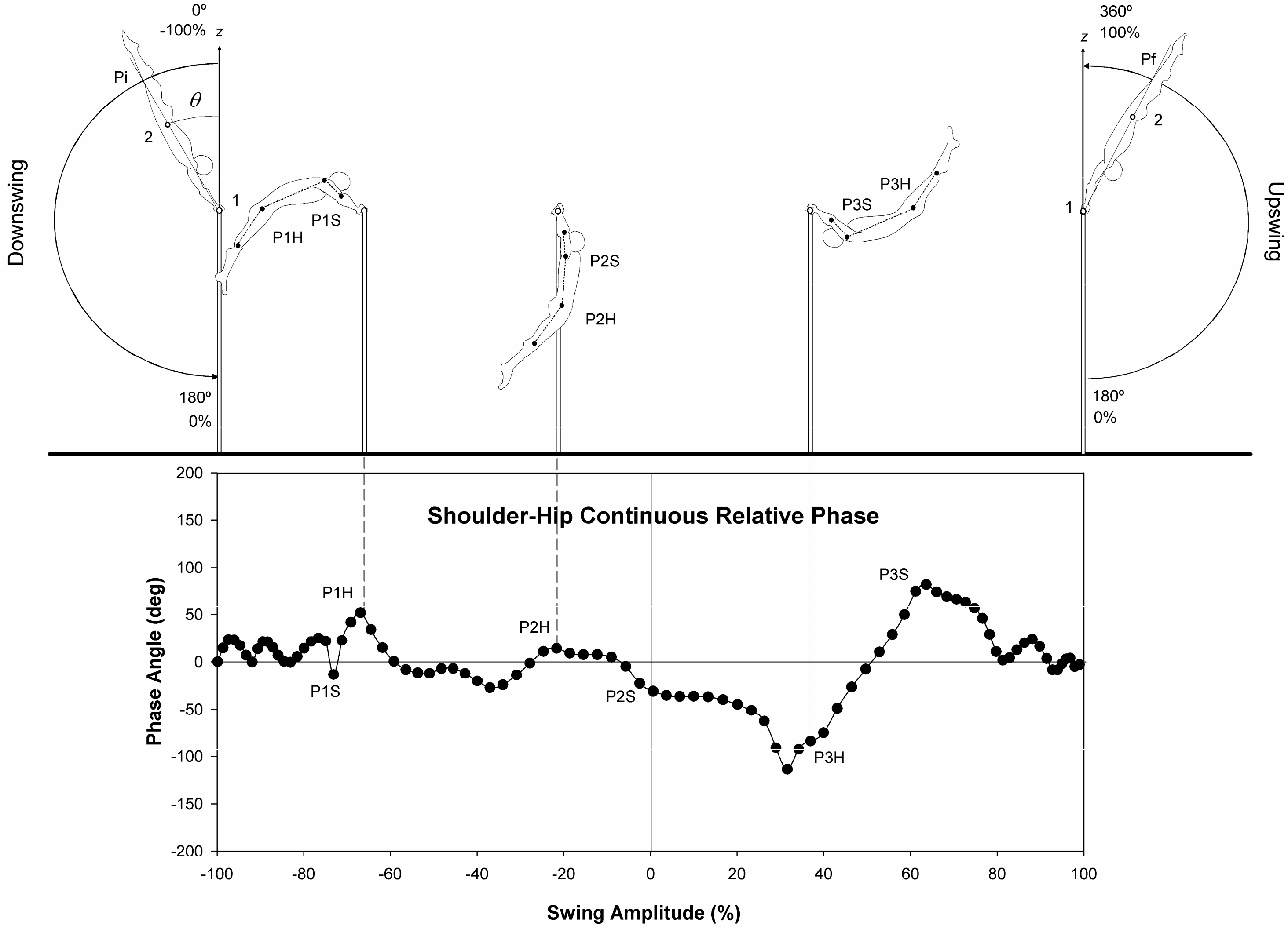

0º
-100%
z
Pi
θ
2
1
Downswing
180º
0%
P1S
P1H
P2S
P2H
P3S
P3H
360º
100%
z
Pf
2
1
Upswing
180º
0%
Shoulder-Hip Continuous Relative Phase
Phase Angle (deg)
200
150
100
50
0
-50
-100
-150
-200
-100
-80
-60
-40
-20
0
20
40
60
80
100
Swing Amplitude (%)
P1H
P1S
P2H
P2S
P3S
P3H

Figure 2

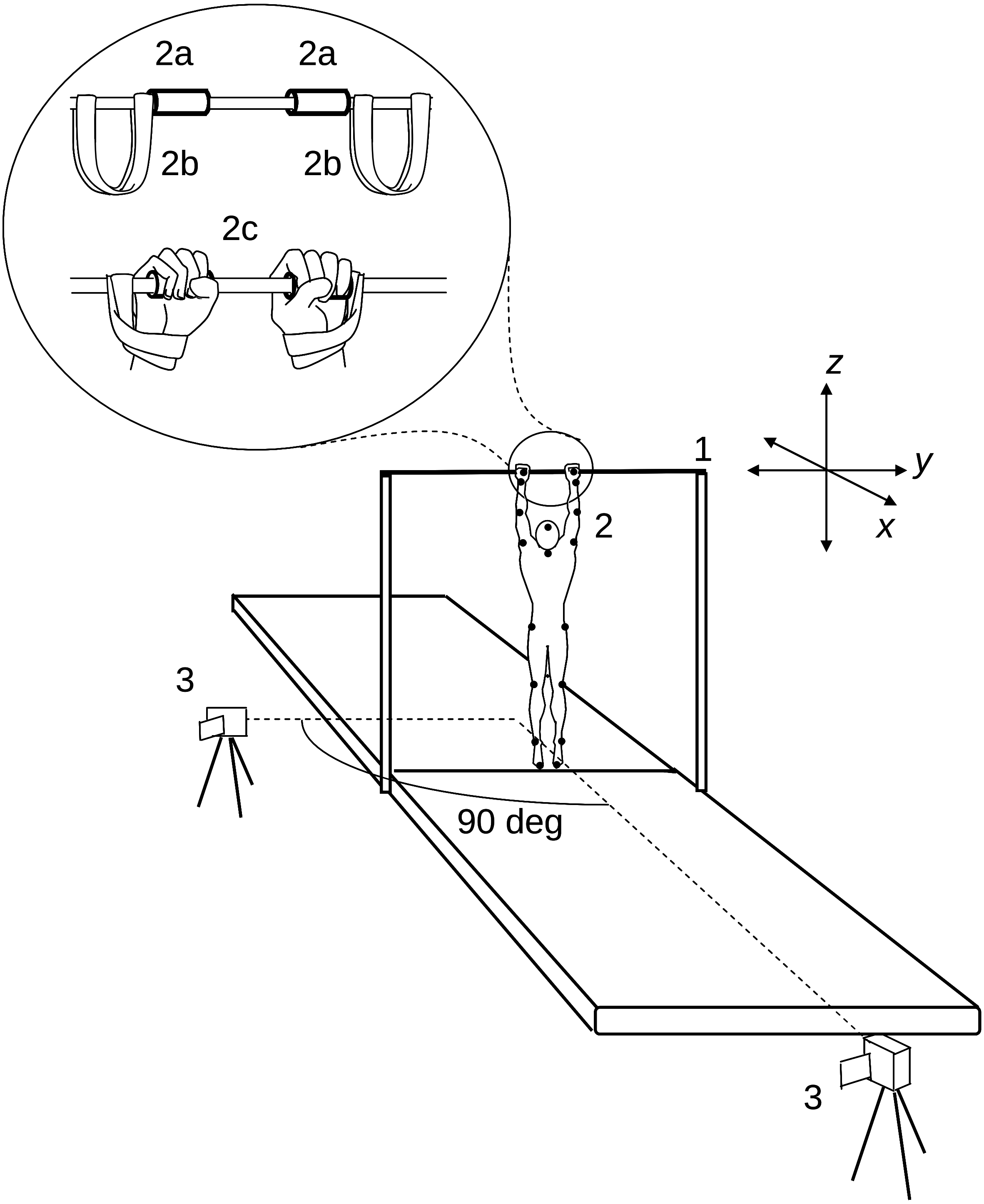
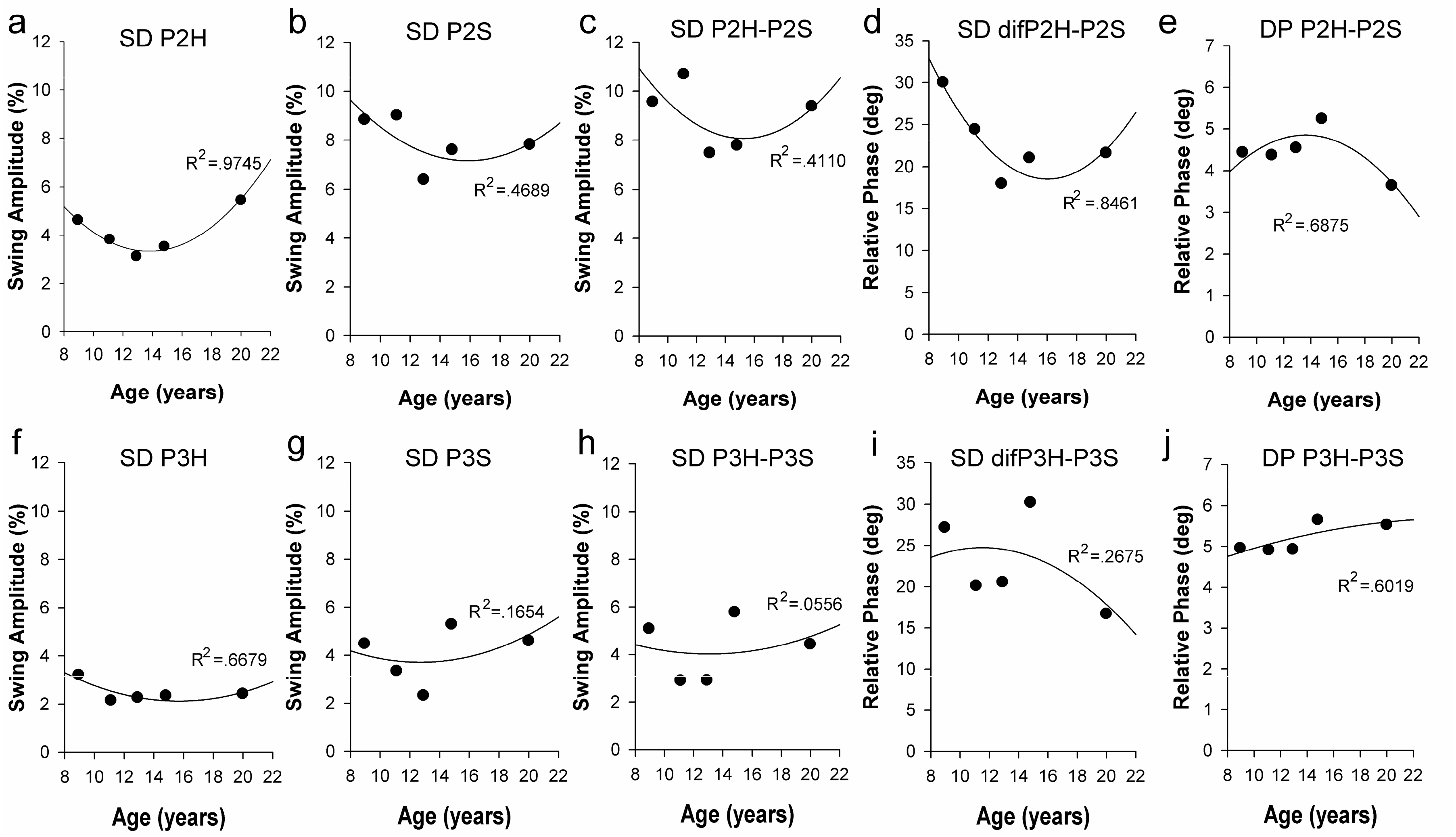


Figure 3


a
SD P2H
R^2=.9745
b
SD P2S
R^2=.4689
c
SD P2H-P2S
R^2=.4110
d
SD difP2H-P2S
R^2=.8461
e
DP P2H-P2S
R^2=.6875
f
SD P3H
R^2=.6679
g
SD P3S
R^2=.1654
h
SD P3H-P3S
R^2=.0556
i
SD difP3H-P3S
R^2=.2675
j
DP P3H-P3S
R^2=.6019
Swing Amplitude (%)
Relative Phase (deg)
Age (years)
0
2
4
6
8
10
12
5
15
20
25
30
35
1
3
7
14
16
18
22

Chapter 7. Discussion and conclusions

Results and Discussion

Studies from this thesis were oriented to help sport and exercise practitioners to develop an appropriate model for understanding how learners acquire and modify motor skills, and in turn improve their intervention during practice sessions. From the numerous sport skills available, it was necessary to select one task to study both periods of the motor-perceptual learning process, that is, the skill acquisition (the individual faces a novel task) and fine tuning period (the individual adjusts a learned task to become successful and efficient). In our research skill acquisition was studied in Chapter 4 and 5 while the fine tuning skill was assessed in Chapter 6. In order to study the motor-perceptual learning process we selected the longswing on the high bar in gymnastics. Longswing learning involves a close association between the improvements in movement performance and coordination (i.e. motor learning) with the ability to correctly perceive and interpret the environment (i.e. perceptual learning). We include in Chapter 4 measurements of performance perception.

Following Dynamic System Theories (DST), learning is a non-linear process characterized by transition phases where variability tends to increase.(Clark et al., 1993; Clark, 1995; Hamill et al., 1999). Therefore, we also analyzed the variability of the performance and coordination. DST understands that movement arises from the relative impact of practice and constraints (organismic, task, and environmental) (Clark, 1995; Clark, 2002; Handford et al., 1997; Holt, 2005; Kugler et al., 1980; Marin et al., 1999; Newell, 1986; Nourrit et al., 2000; Thelen et al., 1994). We focused our research studies in how practice and organismic constraints (a-priori talent and competition age, in the skill acquisition and the fine tuning skill period respectively) impacted movement learning. We assumed in Chapter 4 and Chapter 5 that values closer to experts (high level of skill) represented an advantage to improve movement performance and coordination as a result of practice. In the Chapter 6 we assumed that the longswing is learned and optimized during years of practice. In order to observe most relevant long-term changes, Chapter 6 was designed as a cross-sectional study comparing competition age groups from beginners to experts.

Performance (measurable outcomes of the movements) and coordination (spatial-temporal relationship between segments or joints to achieve movements) were analyzed in our studies to assess motor learning. Focusing in the changes of the longswing performance, three types of variables were used: swing performance (Pi, Pf, and Swing amplitude), swing events (P1H, P2H, P3H, P1S, P2S, and P3S), and swing phases (P1H-P2H, P2H-P3H, P3H-Pf, P1S-P2S, P2S-P3S, and P3S-Pf). It was hypothesized that performance would become more similar to experts with practice (two months in Chapter 4) or increases in expertise (competition age group in Chapter 6). In addition, within the novice cohort in Chapter 4, those subjects with spontaneous talent were expected to experience larger improvements in performance than those with less initial talent.

Findings from the skill acquisition study (Chapter 4) suggested that novice participants improved their performance due to practice independent of their a-priori talent (i.e. initial skill level), but the initial novice group differences remained across time (practice). The average novice swing amplitude achieved after two months of practice was close to 100% and clearly far from that of expert values (200%). Indeed, the fine tuning study (Chapter 6) showed that gymnasts swing amplitude across age groups became similar to expert swing amplitude values from the intermediate group (G3) on. Clearly, great amount of practice and expertise would be necessary to achieve the expert swing amplitude.

Performance was also assessed by the spatial sequence of the critical events. Although swing performance variables (Pi, Pf, and Swing amplitude) were not different between novices groups (NST vs. ST) in the skill acquisition study (Chapter 4), the placement of the events in the downswing differed between groups when examining the practice effect. Concretely, the P2 events critically differentiated the two groups. The ST group maintained or slightly changed the hip (P2H) and shoulder (P2S) maximum extensions. In contrast the P2 events became worse with practice for the NST group despite this group began the study closer to expert values than the ST group. Both groups after practice yielded P2H and P2S values closer to the -27%, that is, a bit sooner but relatively close to the vertical axis. On the other hand, in the fine tuning skill study (Chapter 6) P2 events became progressively closer to the vertical axis from G1 (-15% swing amplitude) to G4 (close to 0% swing amplitude). Interestingly, G5 performed P2 earlier in relation to the vertical. However, given the consistency of the more expert groups performing P3 events in Chapter 4 and 6, it was suggested that: (1) P2 events are less critical for experts, while (2) P3H and P3S executions are critical to maintain the angular momentum in the upswing and improve the swing amplitude and complete the longswing. P3 events were performed progressively later across competition age groups acquiring values of the expert group (G5) in G4. In contrast, after the two-month practice period in the Chapter 4 the novice hip and shoulder maximum flexion in the upswing did not improve.

Interestingly, P2 and P3 evolved differently by groups. Changes in P2 but not in P3 events were observed in the less experienced groups (novice participants). P2 events were performed by novices and beginner groups (G1) earlier than the expert group (G5), while P2H did not differ from G2 to G5. However, G3 showed the largest consistency for the P2H this suggesting that this event is important at this competition level. As one examines P3 events, P3H and P3S were executed similarly to the expert group by the G3 and G4. The largest consistency of the P3H and P3S were achieved by G4 and G5 respectively. Given these results, we would suggest that events are learned successively in agreement with their spatial-temporal performance sequence. Perhaps the different level of consistency of the event placement demonstrated by each group is also informative of this sequence.

Despite the improvements aforementioned in the novice groups, the changes occurred in hip and shoulder P2-Pf phases did not drastically improve the swing amplitude although the values became closer to those of experts. Novice participants maintain an earlier P3 execution after practice, therefore the inertial momentum decrease due to flexing the hip and shoulder also occur too early in the upswing, limiting the subsequent contribution of the functional phase of the shoulder to maintain angular velocity. Given these results and the expert consistency of the P3 events, we would argue that in early stages of learning placement of the functional phases (i.e. events) within the cycle is more critical than duration of the phase per se.

An additional objective in Chapter 4 was to measure changes in the participants' performance level perception after practice. Perceptual results of this article could partially explain the group differences observed in P2 performance. Our results provide suggestive evidence for transference from perception to action in the ST group. Perception of performance and perception of the hip event in the downswing (Pi-P2H) improved only in the ST group while the NST perception did not change. It can be postulated that certain level of perceptual accuracy is needed to demonstrate higher levels of performance, either initially (spontaneous talent) or as a result of practice. However, an alternative view could be defended that of requiring certain level of performance before adequate perception is achieved. Despite, further research will be needed to assess the impact of feedback in the longswing learning. Such research would be informative to the educators or coaches to facilitate the perceptual component of learning during the practice of the longswing.

Improvements in perception only occurred in the downswing. We proposed that visual feedback in the descendent phase of the swing is more familiar. For example, participants saw the floor, poles and cables of the high bar and they were in a more commonly adopted body position. In contrast, feedback became unfamiliar during in the upswing (participants saw the ceiling). Perhaps familiarization with this particular feedback from visual, proprioceptive, and vestibular sensory systems could allow learners to improve the P3 events at a faster rate.

Given our findings in the performance variables of the longswing, we would propose to the educators and coaches to focus their intervention priorities in the event placements rather than in the phases' duration to teach this skill during the period of skill acquisition. The intervention of the practitioners in the event placements should be in agreement with the spatial-temporal performance sequence. That is, first interventions should focus in P1, second direction of the practitioners' assistance would be P2, and finally they would attempt to improve P3. Additionally, practitioners' interventions should incorporate a P3 sequence to lead efforts to hip maximum flexion placement first and then to shoulder maximum flexion placement. Finally, intervention of the educators and coaches should contemplate the perceptual learning of the longswing giving feedback to place events adequately and to familiarize the learner with the particular information when faced with the upswing.

It would be expected to find some changes in coordination that could help explain the modifications found at the level of performance. To explain changes in coordinative learning of the sport skills from DST approach several tools were checked in Chapter 2 and Chapter 3. We selected the continuous relative phase (CRP) to reduce biomechanical data and analyze coordination because the CRP include in one variable (graph) the spatial-temporal relationship of two segment limbs or joints. Despite Chapter 3 concluded that CRP was suitable to adequately analize sport skills coordination, quantitative variables from CRP were necessary to conduct an objective study and compute statistics.

Chapter 5 was designed to assess coordination changes after two-months practice in skill acquisition period (participants faced to longswing for the first time). To address the aims of the study, coordination was defined by the qualitative analysis of the CRP and by using three types of variables: inter-joint reversal points, mean absolute relative phase (MARP), and absolute difference in the continuous relative phase. Within subject variability (intra-trial) was also assessed by deviation phase variables. Changes in coordination in the fine tuning skill period was examined in the Chapter 6. We included the inter-joint reversal points and the absolute difference in the CRP as coordinative variables given the results of the previous research in Chapter 5. In addition, within subject variability (including inter- and intra-trial variability) of the coordination was assessed to characterize the learning stage of the group during the fine tuning period. Inter-trial variability was examined for each variable by the individual standard deviation from the three consecutive swings, while deviation phase in each swing was used to measure intra-trial variability. We analyzed the U-shaped fit of the within subject variability performing the longswing across the competition age groups as proposed by Wilson et al. (2008). It was hypothesized that coordination would become more similar to experts with practice (two months in Chapter 5) or increases in expertise (competition age group in Chapter 6). In addition, within the novice cohort of the skill acquisition study (Chapter 5), those subjects with spontaneous talent for this task were expected to become more consistent and better coordinated than those less talented. It was expected that within subject variability will be larger for the younger competition age groups than intermediate experienced groups, but within subject variability will increase again in the older group.

When skill acquisition period was analyzed concerning the initial skill level of the participants, qualitative analysis of the CRP allow us to define three coordinative patterns (a, b, and c) representing a progressive change to achieve expert coordinative pattern (c). The ST group modified their coordinative pattern after practice moving closer to that of experts, while the effect of practice in the NST group resulted in an even distribution between the three coordinative patterns. We would suggest that a more talented initial skill level of the participants provided an advantage to achieve a more effective coordination mode with practice. However, no significant findings were yielded analyzing the MARP between contiguous events of different joints (P1H-P1S, P2H-P2S, and P3H-P3S).

Differences in coordinative variables for the skill acquisition (Chapter 5) and fine tuning skill (Chapter 6) studies were only found in the inter-joint reversal points. In fact, inter-joint reversal points in the downswing (P1H-P1S and P2H-P2S) critically differentiated the NST group and the ST group when examining practice effects. The ST group reduced the time lag between events of hip and shoulder during the downswing getting them closer to expert values. In contrast, the NST group worsened the two inter-joint reversal points with these points occurring more distant from each other. Our results seem to indicate that the initial skill level could modify the practice effect on the execution of the spatial sequence of the movement. Inter-joint reversal points in the fine tuning skill period showed significant results for the P3H-P3S and a tendency for the P2H-P2S suggesting coordination differences between the beginners group (G1) and the expert group (G5).

In addition, inter-subject variability was analyzed in Chapter 5. The expert group yielded less variability in P3H-P3S than the other two inter-joint reversal points. Due to the consistency of the P3H-P3S in the expert group, we would suggest that our data in the Chapter 5 indirectly support the importance of the time lag between the P3 events in biomechanical terms. In contrast to the experts, the ST group showed less variability in P1H-P1S with a closer execution of the hip and shoulder maximum flexion during the downswing. We interpret these results as a potential motor strategy acquired to ensure the execution of the next event placement. Interestingly, the NST group remained with a large variability and relative distant hip and shoulder events in all inter-joint reversal points P1, P2, and P3 suggesting the lack of a consistent group strategy to accomplish the task.

It is important to note that the absolute differences in CRP between P2H (hip extension) and P2S (shoulder extension) for the expert group yielded smaller values and large group consistency. Therefore, the coordination mode acquired by the expert gymnasts was relatively maintained across P2H-P2S. We suggested that P2H-P2S coordination mode is critical in coordinative terms to allow gymnast to prepare P3 events performance in the adequate placement and time sequence. The ST group was differentially closer to expert before practice than NST group in 3 out of 12 coordinative variables. Interestingly, all those related to P2 events (MARP P2H-P2S, difP2H-P2S, and DP P2H-P2S) while NST was closer to expert mainly in P1 variables (P1H-P1S, difP1H-P1S). We interpret these results as a possible advantage of the ST group performing P2. The consequence of this initial advantage in P2 performance means a larger swing amplitude in the pre-practice and also the possibility to explore solutions around this point in time (P2) resulting in further improvements at post-practice.

Because inter-subject variability can only inform about group strategies, we examined the within subject variability (intra-trial in Chapter 5, and inter- and intra-trial in Chapter 6) to address individual behavioral stability. Indeed, coordination transition phases in learning could be revealed by examining within subject variability as we mentioned before. In the skill acquisition study we observed that intra-trial variability in the ST group increased for the P2H-P2S, while the NST group maintained similar variability values. We suggest that successive actions of the longswing are dependent of the preceding ones. The ST group could improve P2H-P2S due to both, their almost simultaneous action of the hip and shoulder at P1 and the consistency within subject of the P1 inter-joint reversal point. However, P2H-P2S intra-trial variability increased for the ST group despite the improvement of the time lag between these events. Several studies proposed two stages in the process of learning new task: (1) appropriate spatial sequence of the movement, and (2) the dynamic joint control (Chow et al., 2007; Gentile, 1998; Hikosaka, et al., 2002; Hung et al., 2008; Teulier et al., 2006). We interpreted that ST group at P2 represents an example of the two stage learning proposed by these authors. In addition, we would suggest that the a-prior talent also could impact differently the time to exploit their initial behavior and start to change coordination.

In Chapter 6 inter-trial variability was significantly different for the SD P3H-P3S, while a tendency was shown in the intra-variability for the DP P2H-P2S and DP P3H-P3S. Interestingly, G4 showed greatest values of the within subject variability in these variables compared to other groups. In addition, when the U-shaped fit of the within variability was analyzed, two distinct patterns were observed: (1) a U-shaped fit found in graphs obtained from the P2 inter-trial variability variables, and (2) a large deviation for G4 observed in graphs of the inter-trial variability for the P3 variables and both intra-trial variability variables, DP P2H-P2S and DP

P3H-P3S. Only variables of the inter-trial variability for P2 supported the proposal and findings from Wilson et al. (2008). In contrast, the second pattern characterized by a large G4 deviation and tendency of some variables (SD P3H-P3S, DP P2H-P2S, and DP P3H-P3S) for this group to have increased variability suggested a transition point. It has been proposed in the literature that a performer will change motor strategies when the initial behavior does no longer improve the task (Nourrit et al., 2003; Teulier et al., 2006). However, the swing amplitude between G4 and G5 were not statistically different. Therefore, we would suggest an alternative explanation to the G4 variability findings. The transition phase could be due to increased demands of the sport (learning flight elements, dismounts). The process of adapting and practicing the preparatory longswing to face higher demands tasks (flight elements, dismounts) could impact in the motor strategies to perform the regular longswing. It was suggested that after this transition point the expert coordination mode can be adopted.

In summary, our results seem to indicate that P3 event placements and their time lag are important in biomechanical terms to perform maximal swing amplitude (200%). However, the achievement of the adequate placement and time sequence of the P3 events in the skill acquisition period was conditioned to the P2H-P2S coordinative mode. In contrast, in the fine tuning period changes in the P3 coordinative mode was critical to acquire the expert motor strategies. We suggest that the spatial-temporal sequences of the longswing actions appear to be learned before than their dynamic control. Given that successive actions seems to depend of the preceding ones, adequate coordination of the previous action conditioned learning of the subsequent action. For example, adequate coordination mode of the P1 events is required to place correctly P2 events.

In the skill acquisition period to achieve the complete swing (200%), we would propose to the practitioners to focus their intervention first in the placement of the events and later to acquire the adequate coordination mode between hip and shoulder. As aforementioned, intervention of the practitioners should be in agreement with the spatial-temporal performance sequence. Focus the intervention progress first from acquisition of the P1H and P1S placement to learning of hip and shoulder coordination mode in P1H-P1S, then the same intervention sequence occurred in P2, and finally in P3 events. We also suggest increasing attention of the educators and coaches in the P2H-P2S coordination mode to facilitate achieving the complete longswing due to the adequate P3 events placement. In contrast, P3 events will be the focus of the intervention during the fine tuning process to acquire expert coordination mode and allow learning of higher demands tasks (flight elements, dismounts).

Gentile (1998) proposed that learners use external feedback (verbal indications, visual-spatial references) to improve their spatial-temporal sequence of the movement, while internal feedback (proprioceptive and vestibular inputs) is more useful to acquire dynamic control. Following this author, we would suggest to practitioners to alternate their strategies to elaborate the practice sessions in accordance to the learning stage (spatial-temporal sequence or dynamic control acquisition) of the focused events. If the goal of the intervention was to improve the P2 events' placement and P1 coordinative mode, then feedback will be external (from demonstration, manipulation, verbal guide, or visual markers in the environment) for the P2H and P2S placement while internal inputs (for example, designing tasks to evidence the whole body and joints displacements and velocities when leaner perform them) will be used to improve the P1 coordinative mode.

Although the true process of learning cannot be characterized, our study designs let us describe the changes occurred in the skill acquisition and the fine tuning periods concerning organismic constraints (a-priori talent and competition age). Further studies are necessary to assess the complete process of learning and considering longitudinal data from initial trials to the complete longswing acquisition. However, another organismic constraint that could be contemplated as relevant is sex. In our research, sex was used as a covariate and showed significant contribution in the performance and coordination of the P3 events. Although the effect of sex as a covariate yielded relatively little results, it may be worthwhile to further examine the potential differences between males and females in the process of learning the longswing, especially when swing amplitude increases and P3S is near to 50% in the upswing. This is the point where maximal force at the shoulders is applied and females are thought to have relatively less force. Sex differences in anthropometric parameters, strength, flexibility, or motor experiences could affect the learning process, specially in the ascendant phase of the downswing (see Chapter 4 and 5). In addition, it will be interesting to examine the impact of the environmental constraints in the longswing learning. For example: learning swing in other apparatus as asymmetrical bars, rings or parallel bars; and learning swing using handgrips.

The analysis of the skill allowed us to present a proposal of potential constraints to explain performance and coordination improvements. However, speculations of potential causes of improvements in swing perception are more difficult and limited to the skill acquisition period. In this research, the swing perception was only assessed by global variables, that is, perceived relative body and hip positions. These variables did not allow a direct test of different sensory modality contribution to motor-perceptual mapping. Further studies are necessary to assess the influence of each perceptual factor in the swing learning. In addition, development of the methodology to evaluate each perceptual factor will allow us to assess perception of coordination. It will be interesting to apply this methodology to evaluate perceptual learning also in the fine tuning skill period.

Analysis of the longswing performance and coordination modes across the competition age groups allowed us to describe skill learning in two different stages (spatial sequence earlier than coordination mode). This was especially evident by the performance variables rather than the coordination variables. We believe that different levels of performance (swing amplitude) and expertise will be related with specific coordination modes. Given that performance and coordination could be impacted by skill level, future studies should examine skill level and age together as factors of analysis. Another possible cause of the limited findings regarding coordination could be the reduced sensitivity to detect changes of the coordinative variables used in this study. Therefore, it will be important in future research to use more sensitive variables of coordination to analyze the tuning process during skill acquisition.

On the other hand, graphs of the group means of the within subject variability showed qualitatively an interesting transition point, but no significant results in the variability were found. Lack of significance could stem from the use of linear statistics. In fact, learning is not a linear process, and for this reason several authors propose non-linear statistics to analyze variability (Harbourne et al., 2009; van Emmerik et al., 2004).

Regarding the fine tuning skill period, learning has been analyzed across the competition age but skill level could have an impact in the adopted motor strategies. Including skill level and age as factors in future research could allow us to understand better transitions to one stable motor behavior to another. In addition, skill level can be defined by efficacy parameters (i.e. swing amplitude) but also by the efficiency performing the task. It would be interesting to define and include efficiency parameters of the longswing in future research. In the fine tuning studies we also focused in the organismic constraints (competition age). Environmental and task constrain are really important during the fine tuning skill. Environmental constraints are modified when gymnasts progress to practice from straps to handgrips or when female gymnasts are faced with asymmetrical bars. Task constraints can change when the regular longswing is adapted in preparation for another element (flight elements, dismounts). Future researches should attempt to evaluate the adaptation to new environmental and tasks constrains.

On the other hand, movement learning includes motor and perceptual factors. We analyzed perception by global variables, that is, perceived relative body and hip positions. Several tools could be utilized to assess each perceptual factor involved in the longswing (vision, proprioception, and vestibular systems). It will be interesting to conduct research across ages and skill level considering the perceptual factors.

Finally, several practical guides have been proposed in this thesis. Future research should be conducted to analyze the impact of interventions in agreement with our suggestions in the motor-perceptual learning process.

Conclusions

The overarching goal of this thesis was to characterize both periods of learning (skill acquisition and fine tuning process) from a dynamical system theory perspective focusing in the longswing as a sport skill. Additionally, this research of the learning of the swing on a high bar is oriented to help practitioners to develop an appropriate model for understanding how learners acquire and modify motor skills, and in turn, how to improve their intervention during their sessions. Regarding the characterization of the motor learning, we observed that skill level (a-priori talent) can affect the learning process when a person faces a novel task. While swing amplitude is not impacted by the initial skill level, perceptual and motor learning (performance and coordination) in the downswing (from -100% to 0% of the swing amplitude) have larger improvements when initial skill level is closer to expert values. We proposed that P3 events' placement and time lag between hip (P3H) and shoulder (P3S) actions are critical in biomechanical terms, but P2 coordination mode is critical to increase swing amplitude in coordinative terms.

Focusing in the fine tuning skill, our research showed that competition age groups swing amplitude was similar from G3 to G5. However, events are acquired progressively (from G3 to G5) in agreement with their spatial-temporal performance sequence. In contrast, our results only differentiated coordination modes of the beginners (G1) and experts (G5). Interestingly, we observed increased changes in the within subject variability in G4 suggesting a transition point. It was suggested that this transition point could be due to increased demands of the sport (learning flight elements, dismounts). These changes in variability mainly occurred in P3 variables. We proposed that interventions should be focused in P3 to acquire expert motor strategies.

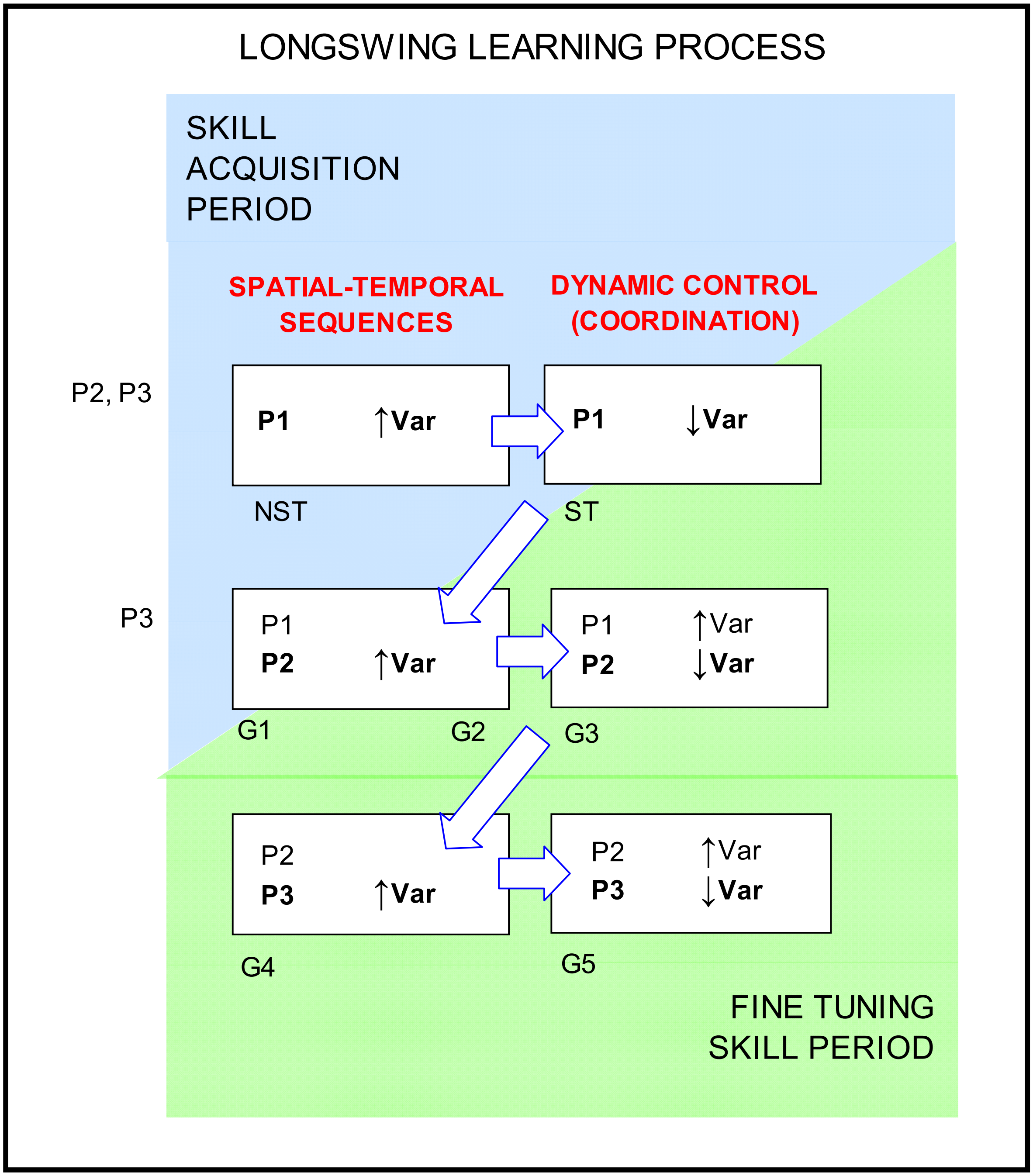


Fig. 4. Sketch of the learning process of the swing in high bar divided by both learning periods (skill acquisition and fine tuning skill). Learning process is characterized by the acquisition sequence of the events (P1, P2, and P3) and behavior of their within subject variability (increase or decrease). In addition, typical group succession (NST, ST, and G1 to G5) is included.

Finally, we proposed a conceptual model to understand the longswing learning process and to improve the intervention of the practitioners (see above Fig. 4). Our results indicated that spatial-temporal sequences of the longswing actions appear to be learned before their dynamic control. In addition, adequate coordination of the previous action conditioned learning of the subsequent action. Decreases in the within subject variability of the coordination variables may indicate that the coordinative mode of the events (P1, P2, and P3) are acquired. After such achievement, the intervention of the practitioner can be focused in the placement of the subsequent event. Given the findings of this thesis, we proposed a learning sequence concerning initial skill level and competition age.

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Annexe 1. Spanish abstracts

Resumen de la Tesis

Changes in swing high bar performance and coordination: skill acquisition and fine tuning skill

Cambios en la ejecución y las coordinaciones del movimiento de balanceo en la barra fija: adquisición y perfeccionamiento

Resumen

Gran número de tareas perceptivo-motoras pueden ser observadas a través de la edad, especialmente si los individuos participan en actividades deportivas. Una persona que se enfrenta a una nueva tarea tiene que elaborar nuevos movimientos para conseguir el objetivo de la tarea (periodo de adquisición de la habilidad). Para ser más eficaz y eficiente, es decir, para ser un experto en una tarea ya aprendida, el sujeto tiene que ajustar los parámetros del movimiento en relación con los condicionantes de la situación (periodo de modificación fina de la habilidad). Desde la perspectiva de la Teoría de los Sistemas Dinámicos (DST), el movimiento surge por el impacto de la práctica y de los condicionantes (del organismo, de la tarea y del entorno). En cuanto a los condicionantes del organismo, el talento a priori es un punto crítico para entender el aprendizaje motor en el periodo de adquisición de las tareas. Además, la edad del ejecutante debe ser considerada en el periodo de modificación fina de la tarea debido a que otros dos procesos se desarrollan a la vez: la maduración biológica y la adquisición de la competencia. La DST también indica que el aprendizaje motor es un proceso no-lineal, por lo que el comportamiento motor estable cambia a otro comportamiento de forma abrupta. Hay una gran posibilidad de movimientos, por ello tuvimos que focalizar nuestra atención en uno. El molino en barra fija ha sido ampliamente estudiado en relación a los parámetros biomecánicos (cinemáticos y cinéticos)

necesarios para su optima ejecución. No obstante, no se habían realizado estudios para examinar como se aprende esta tarea. Por lo tanto, el objetivo general de esta tesis es caracterizar ambos periodos de aprendizaje (adquisición y modificación fina de la habilidad) desde la perspectiva de la DST focalizándonos en el molino de barra fija como habilidad deportiva. Además, esta investigación está orientada a ayudar a los profesionales a desarrollar un modelo apropiado para entender como los practicantes adquieren y modifican las habilidades y a su vez saber como pueden mejorar sus intervenciones durante las sesiones.

Esta tesis está dividida en 7 capítulos, el primero de ellos es una introducción previa una secuencia de cinco artículos (desde el capitulo 2 al 6). Ésta finaliza con una discusión y conclusión general como capítulo final. Los resultados obtenidos en la caracterización del periodo de adquisición de la habilidad mostraron que el nivel inicial de habilidad (talento a priori) puede afectar el proceso de aprendizaje cuando una persona se enfrenta a una tarea nueva. Mientras que la amplitud del balanceo no se vio afectada por el nivel inicial de habilidad, el aprendizaje perceptivo y motor (ejecución y coordinación) en la bajada del balanceo tuvo grandes mejoras cuando el nivel inicial de habilidad era cercano al de los expertos. Nosotros proponemos que la ejecución de la máxima flexión de cadera (P3H) y hombro (P3S) durante la fase de ascenso del molino y el intervalo entre ambas son críticas términos biomecánicos. Sin embargo, el modo de coordinación de la máxima extensión de la cadera (P2H) y hombro (P2S) anterior a los eventos P3 es crítico para incrementar la amplitud del balanceo en términos coordinativos.

En cuanto al periodo de modificación fina de la habilidad, nuestra investigación mostró que la amplitud de balanceo de los grupos de edad de competición era similar desde G3 (12.88±0.50 años) a G5 (19.96±3.37 años). No obstante, los eventos fueron adquiridos progresivamente (desde G3 a G5) de acuerdo con la secuencia espacio-temporal de realización de la tarea. En cambio, nuestros resultados solo diferenciaron los modos coordinativos de los principiantes (G1, 8.92±0.85 años) y los expertos (G5). Hay que destacar, los incrementos observados en los cambios de la variabilidad intra-sujeto en el G4 (14.78±0.57 años) que sugirieron un punto de transición. Nosotros proponemos que este punto de transición puede ser debido al incremento en las demandas del deporte (aprendiendo elementos de vuelo, salidas). Estos cambios en la variabilidad ocurrieron principalmente en las variables de P3. Sugerimos que las intervenciones se deberían focalizar en P3 para adquirir las estrategias motoras que utilizan los expertos. Finalmente, nuestros resultados indicaron que las secuencias espacio-temporales de las acciones del molino en barra parecen aprenderse antes que su control dinámico. Además, la adecuada coordinación de las acciones previas parecía condicionar el aprendizaje de las subsiguientes acciones. Las disminuciones en la variabilidad intra-sujeto de las variables de coordinación pueden indicar que el modo coordinativo de los eventos (P1, P2, P3) está adquirido.

Resumen de los capítulos 4, 5 y 6

Chapter 4. Swing high bar performance in novice adults: Effects of practice and talent

Ejecución del balanceo en barra fija en adultos inexpertos: Efecto de la práctica y el talento

Resumen

El talento a priori del individuo podría influir en la ejecución del movimiento durante su aprendizaje. También los requerimientos de la tarea y los factores perceptivo-motores son críticos en el proceso de aprendizaje. Este estudio describe los cambios en la ejecución del balanceo en la barra fija después de un periodo de dos meses de práctica. 25 participantes inexpertos que fueron divididos por su nivel de talento a priori (talento-espontáneo, ST, y talento-no-espontáneo, NST), y comparados con gimnastas experimentados. Adicionalmente, se valoró el nivel de percepción de su propia ejecución antes y después de la práctica. Definimos tres eventos independientemente para los ángulos articulares de la cadera (H) y el hombro (S), y el intervalo entre eventos consecutivos (fases): el ángulo más pequeño durante la bajada del balanceo (P1H, P1S); el ángulo más grande después de P1 (P2H, P2S); y el ángulo menor durante la subida del balanceo (P3H, P3S). Las variables de rendimiento del movimiento fueron la máxima elevación en la bajada (Pi) y en la subida del balanceo (Pf), y el recorrido total entre las dos (amplitud del balanceo). Los datos fueron recogidos durante las sesiones pre- y post-práctica por dos cámaras de vídeo. Al final de las dos sesiones los participantes dibujaban un esquema para representar su percepción de su propio nivel de ejecución en relación a Pi, Pf y los eventos de la cadera. Los resultados mostraron un efecto similar de la práctica en la amplitud de balanceo para los dos grupos de inexpertos. No obstante, las variables de ejecución y percepción en la bajada del balanceo en el grupo ST mejoraron más debido a la práctica que las del grupo NST. Este estudio sugiere que: (1) las mejoras en la bajada del balanceo fueron más fáciles que

en la subida del balanceo posiblemente a causa de la combinación de la familiaridad de las referencias visuales con el feedback proprioceptivo, y (2) haciendo que el grupo ST pudiese conllevar una mejor o más rápida ganancia en la percepción de su acción comparado con el NST.

Chapter 5. Coordination analysis reveals differences in performance strategies for the swing high bar in novice adults

El análisis de la coordinación revela diferencias en las estrategias de ejecución en el balanceo de barra fija en adultos inexperto

Resumen

Una adecuada coordinación entre la cadera y el hombro es importante para la efectividad de las fases funcionales del molino. Esta investigación describe los cambios de la coordinación inter-articular después de un periodo de práctica del balanceo en barra fija en una muestra inexperto, dividida por el nivel de habilidad inicial (i.e. talento) en dos grupos: talento-espontáneo (ST, n=10, cercanos a la ejecución de los expertos) i talento-no-espontáneo (NST, n=15). La división fue realizada utilizando un análisis de K-means Cluster. Adicionalmente, la ejecución del balanceo post-práctica fue comparada con gimnastas expertos (n=9). La amplitud del balanceo, la coordinación cadera-hombro, y su variabilidad fueron valoradas en las sesiones pre- y post-práctica. Las pruebas ANCOVA mostraron similares efectos de la práctica en el aumento de los balanceos para los ST y NST, un 11% y 18% respectivamente, pero los puntos de inversión inter-articulares (intervalo entre eventos articulares contiguos) en la bajada del balanceo fueron diferentes. El grupo ST debido a la práctica emparejo más ambas articulaciones durante la bajada del balanceo (eventos P1 y P2) que el grupo NST. Además, el grupo ST

incremento la variabilidad intra-sujeto en P2 pero no en P1. El talento inicial podría ayudar a conseguir la correcta secuencia temporal en ambas P1 y P2, lo cual permitiría la exploración de los patrones coordinativos en P2. No obstante, y a pesar del nivel de habilidad inicial, la ejecución del balanceo de subida requerirá ser más finamente coordinado, y por lo tanto, más práctica orientada.

Chapter 6. Skill acquisition of the swing in high bar gymnastics across age

Adquisición de la habilidad de balanceo en la barra fija de gimnasia a través de la edad

Resumen

Durante el proceso de adquisición de una habilidad se debería descubrir una estrategia motora (ejecución y coordinación) efectiva. La coordinación ha sido definida como la relación espacio-temporal estable entre los segmentos de las extremidades y las articulaciones para conseguir el objetivo de la tarea. El descubrimiento de nuevos modos de coordinación puede conllevar que el individuo sufra una transición de una forma estable de coordinación a otra. La alta variabilidad intra-sujeto es característica de un sistema en transición. No obstante, los cambios en la variabilidad intra-sujeto fueron también observados al incrementarse el nivel de competencia. Se sugirió que la variabilidad intra-sujeto en función de la progresión de la habilidad conforma una gráfica en forma U. Las habilidades deportivas representan una situación ideal para valorar cambios en la ejecución, la coordinación, y la variabilidad intra-sujeto en los diferentes niveles de competencia. Nosotros seleccionamos el molino 'regular' en la barra fija de gimnasia como foco de nuestro estudio ya que esta habilidad es identificada como una habilidad básica fundamental.

Dos objetivos principales fueron perseguidos en este estudio: (1) determinar si el grupo de edad de competición (desde los principiantes a los expertos) utilizan diferentes estrategias motoras de ejecución y coordinación del molino, y (2) valorar los cambios en la variabilidad intra-sujeto de la ejecución y coordinación a través de los grupos. Adicionalmente, analizamos el ajuste de los gráficos de la variabilidad intra-sujeto a través de los grupos de edad de competición con la forma U.

Cinco grupos de edad de competición: G1 (8.92±0.85 años); G2 (11.08±0.67 años); G3 (12.88±0.50 años); G4 (14.78±0.57 años) y G5 (19.96±3.37 años) fueron utilizados para clasificar a los participantes (113 gimnastas). Definimos tres eventos independientemente para los ángulos articulares de la cadera (H) y el hombro (S): el ángulo más pequeño durante la bajada del balanceo (P1H, P1S); el ángulo más grande después de P1 (P2H, P2S); y el menor ángulo durante la subida del balanceo (P3H, P3S). Nosotros focalizamos el estudio en P2 y P3 dado que las fases funcionales del molino están definidas por estos eventos.

Tres balanceos consecutivos fueron analizados por cada participante. Describimos la ejecución por la amplitud del balanceo y los eventos del balanceo, mientras que la coordinación fue valorada utilizando los puntos de inversión inter-articulares y la diferencia absoluta en la fase relativa contínua entre eventos contiguos de diferentes articulaciones. También analizamos la variabilidad intra-sujeto de la ejecución y la coordinación. La variabilidad intra-sujeto fue valorada de dos formas distintas: la variabilidad inter-intento (desviación estándar entre los intentos del participante) y la variabilidad intra-intento (los cambios de coordinación en el intento fueron descritos por la desviación de fase).

Los resultados de este estudio sugieren que las estrategias motoras de ejecución cambian a través de los grupos, y que la correcta situación espacio-temporal de los eventos es adquirida sucesivamente en concordancia con su secuencia temporal (primero los eventos P2, segundo P3H y finalmente P3S). El grupo de principiantes (G1) presentaron un modo de coordinación diferente comparado con el grupo de expertos (G5). El grupo G4 mostró un gran incremento de la variabilidad intra-sujeto en las variables de P3 y de variabilidad intra-intento indicando un punto de transición hacia el modo coordinativo experto de G5. Sugerimos dos argumentos distintos para explicar el acontecimiento de este punto de transición: (1) las estrategias motoras adoptadas hasta G4 no mejoraban más el nivel de la habilidad; o (2) el incremento de las demandas del deporte para incorporar el molino en tareas más complejas.

Annexe 2. Acceptance for publication documents

Aceptación para publicación de los artículos

El artículo “El retrato de fase como una herramienta de análisis del comportamiento motor” (capítulo 2 en esta tesis) y el artículo “El ángulo de fase y la fase relativa continua para la investigación de la coordinación motora” (capítulo 3 en esta tesis) fueron aceptados por la revista *Apunts. Educación Física y Deporte* el 11 de Noviembre de 2009. Aún están pendientes de publicación.

E-mail recibido el 11 de Noviembre de 2009 y certificados del director de la revista:

> Att. Dra. Rosa Angulo y Albert Busquets,
>
> Apreciados colaboradores, nos es grato comunicarles que el Consejo Editorial de las revistas Apunts. Educación Física y Deportes (ISSN 1577-4015) y Apunts. Educació Física i Esports (ISSN 0214-8757) ha aceptado sus trabajos "El retrato de fase como una herramienta de análisis del comportamiento motor" y "El ángulo de fase y la fase relativa continua para la investigación de la coordinación motora " para su publicación en las mismas.
>
> Les adjuntamos el correspondiente certificado de aceptación.
>
> Reciban un saludo muy cordial,

INEFC
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JAVIER OLIVERA BETRÁN, como director de *Apunts. Educación Física y Deportes* (ISSN 1577-4015) y *Apunts. Educació Física i Esports* (ISSN 0214-8757), revistas del Instituto Nacional de Educación Física de Catalunya,

CERTIFICA:

Que el artículo "**El retrato de fase como una herramienta de análisis del comportamiento motor.**" **de Rosa Mª Angulo Barroso y Albert Busquets Facibén**, ha sido aceptado por el Consejo Editorial y se encuentra pendiente de publicación. En cuanto tengamos confeccionado el sumario del número correspondiente, se lo comunicaremos.

Y para que conste, firmo este certificado en Barcelona,
a 11 de Noviembre de 2009.

Generalitat
de Catalunya

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Y para que conste, firmo este certificado en Barcelona, a 11 de Noviembre de 2009.

El artículo “Swing high bar performance in novice adults: Effects of practice and talent” (capítulo 4 en esta tesis) fue aceptado por la revista *Research Quarterly for Exercise and Sport* el 7 de Junio de 2009. Aún están pendientes de publicación.

E-mail recibido el 7 de Junio de 2009:

07-Jun-2009

Dear Mr. Busquets:

I am pleased to inform you that your paper 'Swing high bar performance in novice adults: Effects of practice and talent' is accepted for publication in Research Quarterly for Exercise and Sport. Your next step is to prepare the final manuscript that will be published.

Please carefully edit your entire manuscript one final time. This includes removing all track changes, and highlighting. Please append an unblinded title page to the final copy.

Please check to make sure that all aspects of the manuscript conform to APA/RQES format and style requirements including indenting each paragraph, and adding your author information on the title page.

To assist you with this process, I have enclosed a checklist of these requirements. As a part of the final check, please make sure that all your references are correctly presented.

In addition, please prepare the manuscript as stated in the attached “Guidelines for Manuscript Preparation.” It is very important that you prepare everything—in particular tables and figures—according to the guidelines. Doing so will eliminate addition requests for revisions either from our office or during the publishing process.

Please have each author complete and sign the attached release form. Please scan the form and attach it with the final manuscript.

To revise your manuscript, log into http://mc.manuscriptcentral.com/rqes and enter your Author Center, where you will find your manuscript title listed under "Manuscripts with Decisions." Under "Actions," click on "Create a Revision." Your manuscript number has been appended to denote a revision.

You will be unable to make your revisions on the originally submitted version of the manuscript. Instead, revise your manuscript using a word processing program and save it on your computer. Please also highlight the changes to your manuscript within the document by using the track changes mode in MS Word or by using bold or colored text.

Once the revised manuscript is prepared, you can upload it and submit it through your Author Center.

When submitting your revised manuscript, you will be able to respond to the comments made by the reviewer(s) in the space provided. You can use this space to document any changes you make to the original manuscript. In order to expedite the processing of the revised manuscript, please be as specific as possible in your response to the reviewer(s).

IMPORTANT: Your original files are available to you when you upload your revised manuscript. Please delete any redundant files before completing the submission.

Thank you for your fine contribution. On behalf of the Editors of the Research Quarterly for Exercise and Sport, we look forward to your continued contributions to the Journal.

Sincerely,
Dr. Kathleen Williams
Editor in Chief, Research Quarterly for Exercise and Sport
k_willia@uncg.edu

Research Quarterly for Exercise and Sport

Mark G. Fischman
Editor-in-Chief

Sam Logan
Editorial Coordinator

December 28, 2009

Dear Mr. Busquets:

Re: 'Swing high bar performance in novice adults: Effects of practice and talent'

Your manuscript was accepted for publication on June 14, 2009. We now have all we need to place your paper into the publication queue. We will be in contact with you nearer the time of publication with page proofs.

Thank you for your fine contribution. On behalf of the Editors of the Research Quarterly for Exercise and Sport, we look forward to your continued contributions to the Journal.

Sincerely,

Mark G. Fischman

Mark G. Fischman
Editor-in-Chief