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REVIEW

Freezing Degrees of Freedom During Motor Learning: A Systematic Review

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According to Bernstein, the central nervous system solution to the human body's enormous variation in movement choice and control when directing movement—the problem of degrees of freedom (DF)—is to freeze the number of possibilities at the beginning of motor learning. However, different strategies of freezing DF are observed in literature, and the means of selection of the control strategy during learning is not totally clear. This review investigated the possible effects of the class and objectives of the skill practiced on DF control strategies. The results of this review suggest that freezing or releasing the DF at the beginning of learning does not depend on the class (e.g., discrete skill class: football kick, dart throwing; continuous skill class: athletic march, handwriting) or objective of the skill (e.g., balance, velocity, and accuracy), in isolation. However, an interaction between these two skill elements seems to exist and influences the selection of the DF control strategy.

***Keywords*:** joint coordination, motor behavior, motor skill, skill acquisition, task constraints

One of the concerns in the motor behavior area is to understand how the coordination and control of movements are modified during motor skills learning (McDonald, Van Emmerik, & Newell, 1989). Therefore, it is important to understand how a system (human body) with so many independent components (bones, joints, muscles, etc.), which have countless combination possibilities, can be controlled by a single effector system (central nervous system). For Bernstein (1967), the solution to this problem would be mastery over the degrees of freedom (DF), known as the independent components of the control system and the various

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possibilities of its movement (Latash & Turvey, 1996). According to Bernstein (1967), during the initial phases of learning a new skill, the motor system uses a strategy to reduce the many possibilities of skill performance to the minimum number required, and this strategy is denominated by freezing the DF. This condition decreases the possibilities of a relationship between the performance method and reaching the skill goal, which simplifies the control. Posteriorly, influenced by the skill practice effect, the DF is released gradually, providing the performer with conditions to explore a higher number of combinations of independent components and reach the goal by means of different methods.

Among the studies that tested the hypothesis of DF freezing, the study by Newell and van Emmerik (1989) investigated handwriting learning with the nonpreferred hand and observed that, even after much practice, the joint pairs of fist–elbow and elbow–shoulder maintained an organization of movement coupling (freezing) characterized by strong and positive correlation values between these joints. They also analyzed the preferred hand, which naturally had a higher quantity of practice, and verified that the movement coupling was smaller between the joints of this limb, suggesting that the strategy of DF freezing was initially explored in the handwriting learning and that a great amount of practice could cause the DF freeing of the nonpreferred limb. McDonald et al. (1989) analyzed learners in dart throwing and showed that its practice provided a decrease in the correlation values between the fist–shoulder and elbow–shoulder angular velocity, characterizing the release of DF. Other evidence of DF freezing/freeing was also observed in studies with skiing on a simulator (Hong & Newell, 2006; Vereijken, Van Emmerik, Whiting, & Newell, 1992), football kicking (Anderson & Sidaway, 1994; Hodges, Hayes, Horn, & Williams, 2005), the racketball forehand drive serve (Smith, McCabe, & Wilkerson, 2001), volleyball serve (Temprado, Della-Grasta, Farrell, & Laurent, 1997), athletic march (Majed, Heugas, Chamon, & Siegler, 2012), and walking on hands and feet (Sparrow & Irizarry-Lopez, 1987). These studies add support to the hypothesis of utilization of a strategy with a freezing/freeing sequence during the motor skill learning process.

On the other hand, studies with skills of pointing/touching an object on a target (Jaric & Latash, 1999), balancing on a moving platform (Ko, Challis, & Newell, 2003), and kicking a ball over a height barrier to reach different targets on the ground (Chow, Davids, Button, & Koh, 2008) reported contrary evidence on DF freezing at the beginning of learning. An explanation for this is that the initial strategy of DF freezing would not be unique or universal and that reorganization of DF would be dependent on each type of skill, the skill objective, the individual constraints of the individual executing the skill, and the environment where it is realized (Newell & Vaillancourt, 2001). When analyzing balance maintenance on a dynamic platform (Ko et al., 2003), the hip and knee joints demonstrated a larger range of movement (pre = 11°, post = 3° and pre = 9°, post = 3°, respectively) and weak values of correlation between the ankle and hip angles in pre and post practice (pre = 0.1, post = –0.4). These results indicated greater exploration of joint spaces and independent control of these joints in the initial phases of learning, besides being a strategy with a sequence of DF freeing/freezing. Chow et al. (2008) investigated whether strategies used during the practice sessions would be the same for every participant. For this, they evaluated four subjects performing a ball kick over a barrier aiming at different targets on the ground and observed that there was no DF reorganization pattern between the participants. Some participants used strategies with a sequence of DF freezing/freeing, while others used the inverse strategy, reinforcing that DF reorganization could be dependent on each individual constraint.

These divergences in different strategies of DF freezing/freeing could be due to the different characteristics and/or demands of the tested skill, as well as the objectives proposed for the skill in each study. For example, Anderson and Sidaway (1994) and Chow et al. (2008) analyzed discrete skills (kicking in soccer) and found different results, freezing/freeing in the first study and freeing/freezing in the second study. Despite the same skill classification (discrete), these skills differed in their objectives, in which one was to produce greater ball speed and the other greater pass accuracy. It is suggested that skills of the same class, but different objectives, can explore different strategies of DF reorganization.

The general strategy of DF freezing/freeing during motor skills learning is still unclear, which demonstrates the need to review the studies performed to date, to obtain answers to the following important questions: First, is the strategy of DF freezing/freeing related to the learning level of the practice task? Second, does this strategy depend on the skill class practiced (e.g., discrete skill class: football kick, dart throwing, etc.; continuous skill class: athletic march, handwriting, etc.)? Third, is this strategy related to the objective of the practiced skill (e.g., balance, velocity, accuracy)? Finally, is there an interaction between the class and objective of the practiced skill that influences the strategy of DF freezing/freeing used? The purpose of this study was to realize an integrative systematic literature review and verify the effect of the skill class practiced and objectives in the DF control strategy, to answer these questions.

Methods

Search Strategy

The information search was realized using the following databases: PubMed, Embase (ScienceDirect), Web of Science, Scopus, and SPORTDiscus (EBSCO). The terms were combined according to the following combination:

(a) Practice of motor skill OR Practice effect OR Skill learning OR Learning a new Skill

(b) Inter joint coordination OR Multi joint coordination OR coordination changes

(c) Practice of motor skill OR Practice effect OR Skill learning OR Learning a new Skill) AND Inter joint coordination OR Multi joint coordination OR coordination changes

Inclusion and Exclusion Criteria

The inclusion criteria were as follows: (a) original studies about motor skills practice, (b) published in English, (c) participants aged between 16 and 50 years, and (d) studies that analyzed the practice effect on DF freezing (Bernstein, 1967).

The exclusion criteria were as follows: (a) studies comparing novice and experienced individuals, as they did not verify the practice effect in DF freezing; (b) studies with special populations (e.g., Down syndrome, coordination deficit disorder); and (c) studies that analyzed only the dynamics and dimensional aspects of coordination, as this approach seeks to determine the variables that may represent the state of the organization of the system dynamics. In addition, it is possible to achieve a change in the dimension of system dynamics with learning, even if there is no change in the number of mechanical DF in motion (Newell & Vaillancourt, 2001). The results and search strategies used for each database are described in Table 1. Figure 1 illustrates the stages adopted for the selection and inclusion of studies in this review, according to the PRISMA Statement (Liberati et al., 2009; Moher, Liberati, Tetzlaff, & Altman, 2009).

Results

The selected studies were published between 1987 and 2013 in *ActaPsychologica* (Chow et al., 2008), *Human Movement Science* (Jaric & Latash, 1999; Ko et al., 2003; Majed et al., 2012; Newell & van Emmerik, 1989), *Perceptual and Motor Skills* (Didier, Li, & Magill, 2013; Smith et al., 2001), *Journal of Motor Behavior* (Hong & Newell, 2006; McDonald et al., 1989; Sparrow & Irizarry-Lopez, 1987; Vereijken et al., 1992), *Ergonomics* (Hodges et al., 2005), and *Research Quarterly for Exercise and Sport* (Anderson & Sidaway, 1994).

Table 2 shows the skills practiced, sample characteristics, total amount of practice, measures used, and a summary of the main results of each study. Majority of these selected studies had young adult participants (18–35 years) and only one study included higher age range participants (21–49 years) (Smith et al., 2001). Among the 13 studies that compose this review, the first works to test the effects of practice in DF freezing are dated from 1987 to 1989 (McDonald et al., 1989; Newell & van Emmerik, 1989; Sparrow & Irizarry-Lopez, 1987) and the most recent work

Table 1 Total of Studies Acquired in Each Database, the Filters Used, and the Total Studies After Filtering

Database	Total	Filters used	Total after filtering
PubMed	148	Not used	148
Embase (ScienceDirect)	38.149	a. Publication title (human movement science and social science and medicine) b. Topic (human movement, movement, motor, practice, relative phase, and experiment)	95
Web of Science	553	a. Categories (sport science and multidisciplinary sciences)	99
Scopus	85	Not used	85
EBSCO (SPORTDiscus)	19	Not used	19

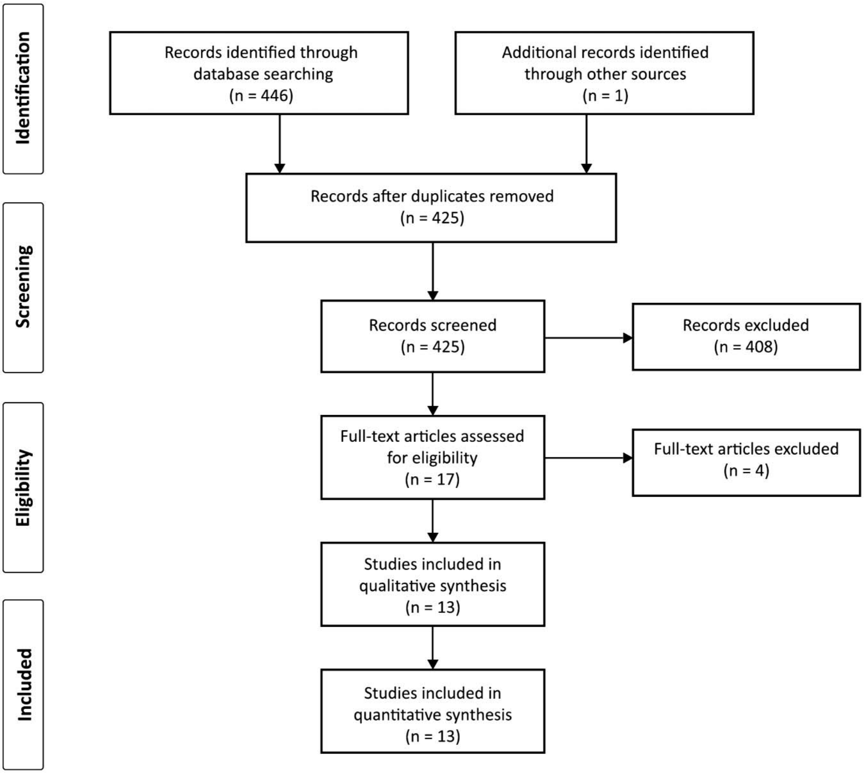

Figure 1 — Stages adopted on the systematic search.

was published in 2013 (Didier et al., 2013). Two studies tested everyday skills, such as pointing/touching an object on a target (Jaric & Latash, 1999) and handwriting (Newell & van Emmerik, 1989). Nine studies tested sports skills such as skiing on a simulator (Hong & Newell, 2006; Vereijken et al., 1992), football kicking and passing (Anderson & Sidaway, 1994; Chow et al., 2008; Hodges et al., 2005), racketball forehand drive serves (Smith et al., 2001), athletic march (Majed et al., 2012), and throwing darts at a target (Didier et al., 2013; McDonald et al., 1989). The other studies analyzed skills such as balancing on a moving platform (Ko et al., 2003) and walking on hands and feet (Sparrow & Irizarry-Lopez, 1987).

Among the forms used to measure DF freezing, the joint range of motion (JROM) (Anderson & Sidaway, 1994; Chow et al., 2008; Didier et al., 2013; Hodges et al., 2005; Ko et al., 2003; Majed et al., 2012; Smith et al., 2001; Vereijken et al., 1992) and cross correlation (CC) between the joint pairs (Chow et al., 2008; Didier et al., 2013; Hodges et al., 2005; Ko et al., 2003; McDonald et al., 1989; Newell & van Emmerik, 1989; Sparrow & Irizarry-Lopez, 1987; Vereijken et al., 1992) were the most commonly used. Thus, these two measurement strategies will receive more attention in the following sections of this review. In addition, Table 2 presents the sample size in each study and the amount of

Table 2 Characteristics of the 13 Studies Reviewed

Authors	Skills	Sample	Total amount of practice	Measurements	Main results
Sparrow and Irizarry-Lopez (1987)	Walk on hands and feet	5 men (20–27 years)	20	CC and AAG	Coordination pattern alterations between the thigh and leg show the emergence of more independent control after the practice session.
Newell and van Emmerick (1989)	Handwriting	5 men and 5 women (20–34 years)	10,000	CC, PPG, and PTG	The post practice CC values show that the nonpreferred hand joint was more organized as a fixed unit than the preferred hand joint.
McDonald et al. (1989)	Dart throwing	5 men (19–30 years)	250	CC	The high positive CC values of the nonpreferred limb showed that in conditions of low practice experience the DFs behave as a fixed unit.
Vereijken et al. (1992)	Skiing on a simulator	5 men (20–32 years)	140	JROM and CC	The DF freezing seems to be a general strategy in complex skills acquisition. However, the DF release seems to be skill dependent.
Anderson and Sidaway (1994)	Football kick	5 men and 1 woman (18–22 years)	400	TRM, JROM, PTG, and AAG	Greater JROM and the emergence of a new coordinative structure made possible increases in velocities generated by hip and knee, reflecting greater foot velocity.
Jaric and Latash (1999)	Pointing at a target	5 men and 1 woman (21–30 years)	310	PRAV	Less involvement of fist joint in final sessions of practice, compared with the initial session, suggested a reorganization attempt and an exploration of a greater number of DF and a nonfreezing in the initial phase of practice.
Smith, McCabe, and Wilkerson (2001)	Racquetball service	10 women (21–49 years)	420	JROM and PCM	The JROM of trunk and hip rotation increased according to practice, indicating exploration of a greater number of DFs in the final sessions.

(continued)

Table 2 ***(continued)***

Authors	Skills	Sample	Total amount of practice	Measurements	Main results
Ko et al. (2003)	Balance on a mobile platform	6 men (22–27 years)	40	JROM, CC, and PC	After practice, the coordination pattern assumed to maintain the balance was to reduce the number of available DFs and minimize the JROM.
Hodges et al. (2005)	Football kick	1 man (26 years)	425	JROM and CC	Decrease in DF after the first session of practice can indicate a need for the learner to reach some consistence in performance, before exploring a greater number of DFs and controlling them.
Hong and Newell (2006)	Skiing on a simulator	5 men (16–24 years)	140	MRCM and PC	Greater range of motion after practice and evidence of different coordination pattern between the superior and inferior parts of the body, reinforce the influence of the task and the individual constraints on the determination of movement pattern.
Chow et al. (2008)	Football kick	4 men (27 years)	570	JROM, CC, and AAG	Different alterations in coordination pattern of the participants show that DF exploration is dependent on the constraints, not only of the task, but also of the individual.
Majed et al. (2012)	Athletic march	7 men (23 years)	7	JROM and RPM	Faster movement reorganization in initial phases of practice, greater hip JROM in final phases, and as a task instruction, less elbow JROM in final sessions.
Didier et al. (2013)	Dart throwing	26 women and 6 men (22 years)	480	JROM and CC	Participants showed an increase in the range of motion during the practice and developed a pattern of control adapted to the environment and task constraints.

CC = cross correlation; AAG = angle–angle graphic; PPG = position–position graphic; PTG = position–time graphic, JROM = joint range of motion; PRAV = pick range of angular velocity; PCM = positive contribution of movement; MRCM = movement range of center of mass; PC = principal components; TRM = temporal relation of movement; RPM = relative phase of movement; DF = degrees of freedom.

practice performed by the participants. With respect to the JROM, only one study assessed a sample size involving more than 10 participants (Didier et al., 2013).With respect to the CC, the amount of practice varied between seven and 10,000 repetitions (Majed et al., 2012; Newell & van Emmerik, 1989).

The main results presented in Table 2 show that nine studies demonstrated evidence of a strategy of DF freezing at the beginning of learning (Anderson & Sidaway, 1994; Didier et al., 2013; Hodges et al., 2005; Hong & Newell, 2006; Majed et al., 2012; McDonald et al., 1989; Smith et al., 2001; Sparrow & Irizarry-Lopez, 1987; Vereijken et al., 1992). Didier et al. (2013) observed an increase in shoulder, elbow, and fist JROM after 480 repetitions of dart throwing. Anderson and Sidaway (1994), analyzing a soccer kick before and after a practice period of 300–400 repetitions, verified lower values of JROM of hip and knee joints at the beginning of practice. Hodges et al. (2005) also analyzed a soccer kick, and the results at the beginning of learning revealed lower hip JROM and strong CC values between the movements of the ankle–knee, hip–knee, and ankle–hip. Lower values of JROM and strong CC values between pairs of joints are characteristics of DF freezing and the search for a strategy that simplifies the control to execute the skill to be learned.

Table 2 also presents three studies that, differently, provided evidence of DF release in the initial phase of learning (Chow et al., 2008; Jaric & Latash, 1999; Ko et al., 2003). Chow et al. (2008) verified that the knee and hip JROM were lower at the beginning of learning in the pass in soccer. However, the CC values of hip–knee and ankle–hip movement before the practice were lower than postpractice, indicating a decoupling between these two joints in the initial phase of learning. Ko et al. (2003) when analyzing learning of balance maintenance on a moving platform, observed that the JROM of the neck, hip, and knee were higher at the beginning of practice, when compared with postpractice and that the DF freezing was explored in the final sessions of learning. One study did not verify significant differences in the reorganization of the DF during handwriting practice with the non-preferred hand, which remained frozen throughout the experiment (Newell & van Emmerik, 1989). Nevertheless, when compared with the preferred limb, it is suggested that a great amount of practice could alter the reorganization of the DF of the nonpreferred limb, with the release of DF similar to the one verified in the preferred hand. The effect of practice on the strategies of DF control was also observed by Hodges et al. (2005) after assessments every 10 days of football kick practice. The authors observed that the hip DF was frozen gradually between Day 1 and Day 5. With the increase in the number of sessions between Day 6 and Day 10, the DF of this joint demonstrated reorganization with a DF freezing/freeing sequence.

Joint Range of Motion

Increases in JROM values are understood as a release and exploration of a higher number of DFs available in the motor system (Smith et al., 2001; Vereijken et al., 1992). Six of the eight studies that used this variable to analyze DF freezing found an increase in JROM in the process of the final phase of learning, when compared with the first measure obtained at the beginning of practice, showing greater utilization of DF in the later phase of learning (Anderson & Sidaway, 1994; Didier et al., 2013; Hodges et al., 2005; Majed et al., 2012; Smith et al., 2001; Vereijken et al., 1992). Similar results were found in the study of Hodges et al. (2005), who measured the JROM everyday intended for practice and found reductions during the first half of the learning period, followed by an increase in the second half. This fact shows that DF reorganization in the learning process depends on the amount of practice. Different to expected, Ko et al. (2003) analyzed a continuous skill that had the objective of balance maintenance and showed reductions in neck, hip, and knee JROM and an increase in ankle JROM during practice. As the corrections in posture (balance) maintenance occur faster in the ankle joint (Horak, 2010), the DF of this joint was released while the other DF joints were frozen.

Cross Correlation

Values close to zero suggest greater independence of the control and coordination between the joints analyzed. In addition, it also suggests a release and higher number of DFs available (Hodges et al., 2005; Vereijken et al., 1992). Six of the eight studies that evaluated the freezing/freeing of DF by means of this measurement method reported alterations in the CC values after the practice period. In the Ko et al. (2003) study, the task required balance maintenance on a movement platform, and a reduction in CC values was observed only between pairs of joints of the ankle–knee, while the hip–knee and ankle–knee did not present any changes. These results support the proposal of using the ankle joint for the necessary control and corrections to balance maintenance. Newell and van Emmerik (1989) found that the CC values of the wrist–elbow and elbow–shoulder joints motions of the nondominant limb were significantly higher compared with those in the dominant limb. After 10,000 repetitions of handwriting practice by the nonpreferred limb, these authors verified a tendency to reduce CC of the most proximal joints (although nonsignificant). These results show the utilization of a dependency strategy of control between the joints. This movement organization of the nondominant hand suggest that in more complex skills such as writing, a greater number of practice repetitions is necessary to change the DF reorganization.

The previously mentioned results show that analysis only by the practiced skill is not sufficient to identify a behavior pattern, which led to analysis of the classification and objective of each skill. Table 3 presents a classification based on the temporal aspects and motor skills organization analyzed by the studies. Table 3 also presents classification of the proposed objective for each skill, according to the methods description of each study and the results that were favorable or contrary to the DF freezing hypothesis. Six studies evaluated continuous skills (Hong & Newell, 2006; Ko et al., 2003; Majed et al., 2012; Newell & van Emmerik, 1989; Sparrow & Irizarry-Lopez, 1987; Vereijken et al., 1992) and seven studies evaluated discrete skills (Anderson & Sidaway, 1994; Chow et al., 2008; Didier et al., 2013; Hodges et al., 2005; Jaric & Latash, 1999; McDonald et al., 1989; Smith et al., 2001). Some of these studies evaluated tasks of the same classification, discrete skills (Anderson & Sidaway, 1994; Chow et al., 2008), and showed divergent results, freezing/freeing of DF in one skill learning and freeing/freezing in another. These differences in the results seem to occur due to different objectives proposed, such as greater ball velocity during kicking (Anderson & Sidaway, 1994) and movement accuracy to hit the ball at a target

Table 3 Classification of Skill and Objective in All 13 Studies Revised

Skill	Authors	Task objective	Positioning
Continuous	Sparrow and Irizarry-Lopez (1987)	Accuracy	Favorable to the DF freezing hypothesis
	Newell and van Emmerick (1989)	Accuracy	Favorable to the DF freezing hypothesis
	Vereijeken et al. (1992)	Balance, accuracy, and velocity	Favorable to the DF freezing hypothesis
	Ko et al. (2003)	Balance	Against the DF freezing hypothesis
	Hong and Newell (2006)	Balance, accuracy, and velocity	Favorable to the DF freezing hypothesis
	Majed et al. (2012)	Accuracy	Favorable to the DF freezing hypothesis
Discrete	McDonald et al. (1989)	Accuracy	Favorable to the DF freezing hypothesis
	Anderson and Sidaway (1994)	Velocity	Favorable to the DF freezing hypothesis
	Jaric and Latash (1999)	Accuracy and velocity	Against the DF freezing hypothesis
	Smith, McCabe, and Wilkerson (2001)	Velocity	Favorable to the DF freezing hypothesis
	Hodges et al. (2005)	Accuracy	Favorable to the DF freezing hypothesis
	Chow et al. (2008)	Accuracy	Against the DF freezing hypothesis
	Didier et al. (2013)	Accuracy	Favorable to the DF freezing hypothesis

DF = degrees of freedom.

from different distances (Chow et al., 2008). Therefore, there seems to be a relationship between the objective to be reached and the practiced skill class, which could influence the DF freezing and release at the beginning of learning. These two studies suggest that when the objective of a discrete skill is movement accuracy, freezing the DF throughout the learning process to gain precision could be the strategy to explore. On the other hand, if the objective of the discrete skill is maximum velocity production, releasing the DF during learning could be the selected strategy to ensure greater ball velocity.

Among the proposed objectives for the skills of each study, accuracy was the aim in six studies (Chow et al., 2008; Didier et al., 2013; Hodges et al., 2005; Majed et al., 2012; McDonald et al., 1989; Newell & van Emmerik, 1989) and velocity in four studies (Anderson & Sidaway, 1994; Hong & Newell, 2006; Smith et al., 2001; Vereijken et al., 1992). One study proposed accuracy and velocity together as the objective (Jaric & Latash, 1999), two studies proposed the objective of accuracy in combination with velocity and balance maintenance (Hong & Newell, 2006; Vereijken et al., 1992), and one study proposed only balance maintenance as the objective (Ko et al., 2003).

The joint analysis of the classification and objective of each skill showed that three of the six studies evaluated continuous skills aimed at accuracy and all of them positioned themselves in favor of DF freezing at the beginning of learning (Majed et al., 2012; Newell & van Emmerik, 1989; Sparrow & Irizarry-Lopez, 1987). Among the other studies with continuous skills, two studies included the combined objective of accuracy, velocity, and balance, and both studies showed that DF freezing occurred at the beginning of learning (Hong & Newell, 2006; Vereijken et al., 1992). The Ko et al. (2003) study also analyzed a continuous skill, but with the objective of balance maintenance and the results were contrary to DF freezing at the beginning of learning. This could have occurred as this study worked with a single skill objective (balance) and not a combination of two or more objectives (balance, velocity, and accuracy) as in the other studies. Thus, the DF reorganization during balance maintenance in studies with combined objectives may have been influenced by the other objectives, the velocity and/or accuracy, justifying the strategy difference in the DF reorganization.

When analyzing studies with discrete skills, it was noticed that four studies had accuracy as the objective (Chow et al., 2008; Didier et al., 2013; Hodges et al., 2005; McDonald et al., 1989). Of these studies, three studies showed that there was DF freezing at the beginning of learning. The exception was the Chow et al. (2008) study with a pass above the head in football. In this study, the participants performed the pass over a barrier positioned 2 m above the ground. It is probable the skill practiced was not new to the participants, as most of them would have experienced situations of kicking an object over an obstacle. The velocity was the objective in two studies (Anderson & Sidaway, 1994; Smith et al., 2001), and both demonstrated a favorable position regarding DF freezing at the beginning of learning. Only one study had the objective of combining accuracy and velocity (Jaric & Latash, 1999), and was contrary to DF freezing. Thus, with the exception of the Chow et al. (2008) study, studies with the same skill class and same objective to be reached showed the same DF organization at the beginning of learning and similar positioning with respect to the DF freezing hypothesis.

Discussion

Studies on the control of the DF in motor skills learning started in 1987 (Sparrow & Irizarry-Lopez, 1987), and a significant number of studies have investigated this issue with different tasks. The Majority of these studies showed that at the beginning of the motor skills acquisition process, the strategy of DF freezing is explored. This strategy is characterized by smaller JROM and by strong CC between pairs of joints that form rigid units and that behave in a coupled manner. These initial characteristics suggest that the motor system organizes itself to simplify the control to perform the designated task (Anderson & Sidaway, 1994; Majed et al., 2012; Vereijken et al., 1992). In contrast, some research has evidenced smaller JROM and strong CC at the end of learning, suggesting that DF freezing does not only occur in the initial sessions of practice (Chow et al., 2008; Jaric &

Latash, 1999; Ko et al., 2003), and this movement control strategy is not universal. Due to the divergence between the results, this integrative review was elaborated using the theme multijoint coordination and interjoint coordination to investigate the changes in coordination observed in the DF. Four questions were established: Is the freezing/freeing DF strategy related to the learning level in the practice task? Does this strategy depend on the practiced skill class? Is this strategy related to the objective of the skill practiced? Is there an interaction between the practice skill class and its objective that may influence the strategy sequence of DF freezing/freeing used?

In relation to the first question, the DF freezing/freeing strategy seems to have a relation with the learning level in the practiced task, which is related to the amount of practice performed. Hodges et al. (2005) analyzed the same individual learning a football kick daily. DF progressive freezing was observed until the first half of the practice period (i.e., hip JROM reductions), followed by a release in the second half of the practice period (i.e., hip JROM increase). These results show that if the analysis had been stopped in the middle of the study, the final conclusions on the DF control strategy would have been inverse. Newell and van Emmerik (1989) verified that 10,000 handwriting practice repetitions with the nonpreferred hand were insufficient to change the DF control strategy and alter the CC value between the fist–elbow and elbow–shoulder. However, the handwriting analysis with the preferred hand revealed that the DF of this limb was released compared with the nonpreferred limb. Again, if the tested hand performed the same amount of practice compared with the dominant hand, the strategy of control could be changed and similar to the preferred hand. The use of an experienced group as a parameter, similar to the study of Anderson and Sidaway (1994), would help to avoid final errors in conclusions about changes in the DF control of learners, mainly in complex skills such as handwriting, which seem to require greater practice for DF reorganization to occur.

Another factor that must be considered, related to the learning level or the amount of practice, is the transfer of learning effect. The learning transfer to other contexts, tasks, and body limbs seems to play a role and, probably, is one of the main factors responsible for the different results found between the studies. If the learner has few motor experiences in tasks similar to the desired one, the strategy of freezing DF would be seen. However, if the learner has already accumulated experiences with similar motor tasks, even if a new motor task is practiced, the release DF strategy would emerge (Chow et al., 2008). Therefore, it is important to consider the motor repertory and the intrinsic tendencies or constraints of the learner (Kelso, 1995). This learning transfer can also help us to understand how different learners with the same level of performance in a new task could present different strategies of control (freezing–releasing). Despite the effect of the amount of practice, the strategy of control has also been shown to depend on the class and objective of the motor class.

The answers to the second and third questions of this review are displayed in Table 3. The second question is related to a motor skill control class, and the testing of discrete motor skills confirmed the hypothesis of the DF freezing/freeing sequence in five studies (Anderson & Sidaway, 1994; Didier et al., 2013; Hodges et al., 2005; McDonald et al., 1989; Smith et al., 2001), while two studies showed the DF freeing/freezing sequence (Chow et al., 2008; Jaric & Latash, 1999).

All the discrete skills studies with the task goal required to perform the movement as fast as possible show results favorable to DF freezing/freeing (Anderson & Sidaway, 1994; Smith et al., 2001). When accuracy was the objective analyzed in isolation, almost every study showed favorable results to the strategy of DF freezing/freeing (Didier et al., 2013; Hodges et al., 2005; McDonald et al., 1989).

The Chow et al. (2008) study used the skill of passing a football over a barrier, a skill that involves the control of great number of DFs, which increased the demand of the task control. This task characteristic can first lead to a more released DF by the subjects and, with learning, freezing the DF to gain precision in the task. Another possible explanation is that only four subjects were analyzed in this study, which could prejudice generalization of the results, although it could also be related to the total practice attempts performed (570 repetitions). This author, as well as the majority of authors of the reviewed studies, do not state whether the amount of practice was sufficient to provide the skill learning proposed. As mentioned previously, a factor that could help in understanding which strategy of DF reorganization is indeed performed in execution of the skill analyzed by Chow et al. (2008) is the use of an experienced group that has had many years of practice. The result difference in this study, according to the authors, could also be due to the fact that the proposed skill was not completely new to the participants, and they had some previous experience in similar movements to perform the pass over in football. This may have provided learning transfer between similar skills and allowed the participants to start the research with a DF organization close to ideal, to reach the objective of this skill. However, Jaric and Latash (1999) showed another particularity, as precision of touching an object as fast as possible was required, which also increased the control demand in the task when compared with others that presented only an objective (precision or velocity). In this final study, there was an interaction of the skill class and task objective.

In studies that tested the continuous motor skills, five confirmed the hypothesis of the DF freezing/freeing sequence (Newell & van Emmerik, 1989; Sparrow & Irizarry-Lopez, 1987), and only the Ko et al. (2003) study showed an opposite result. Once more, there was interaction between the class and objective of the task. Every result that requested precision with a continuous skill, confirmed the hypothesis, and only the Ko et al. (2003) study, where the task objective was balance maintenance on a dynamic platform, did not confirm the hypothesis. It is probable, the fact that the subjects did not have to develop velocity and accuracy could have cooperated so that there was no need for exploration of a greater DF number during the learning process. However, the lack of studies with continuous skills with an objective isolated from balance does not allow comparisons between studies to confirm if the reorganization strategy of DF evidenced in the Ko et al. (2003) study will always be used in continuous skills with an objective isolated from balance.

These results show that the task class is a factor that predominates in DF hypothesis testing, but the effect is mediated by the task objective, answering the fourth question of this review. One possibility is that the strategy used in skills with similar classifications and objectives occurs due to similarity in temporal structures of skill and due to constraints imposed by the task objectives. Therefore, when a temporal structure is the same in two different skills, the joints responsible for the movement are controlled and coordinated in a similar way in every situation in which the objective or the set of objectives are the same.

Last, further studies are needed that analyze combinations of skills with similar classifications and objectives to the studies that did not confirm the hypothesis of a DF freezing/freeing sequence. It is necessary to verify if DF reorganization would be the same as observed in these experiments and confirm the existence of the relationship between the skill class and task objective on the determination of the strategy of DF control in the learning process of motor skills.

Conclusion

The DF freezing/freeing strategy seems to have a relation with the learning level of the practice task, with the most complex skills needing a greater amount of practice so that reorganization of the control of DF can be evidenced. A different conclusion may occur in cases where the amount of practice is not ideal for the proposed skill learning, and an expert group could be a strategy for this control. Freezing or freeing of DF at the beginning of learning does not depend on the skill class to be practiced or the task objective to be performed in isolation. However, there seems to be an interaction between the skill class and its objective that influence determination of the DF control strategy. This review showed that the studies that analyzed skills of the same class with the same objective presented similar positioning about the DF freezing/freeing strategy. However, due to small number of studies in literature, new experiments that take into consideration both analyses (skill class and skill objective) are necessary to confirm this relationship, particularly studies including discrete skills with the objective of movement velocity and accuracy, and continuous skills with the objective of balance maintenance.

References

Anderson, D.L., & Sidaway, B. (1994). Coordination changes associated with practice of a soccer kick. *Research Quarterly for Exercise and Sport, 65*(2), 93–99. PubMed ID: 8047712 doi:10.1080/02701367.1994.10607603

Bernstein, N.A. (1967). *The co-ordination and regulation of movements*. Oxford, UK: Pergamon.

Chow, J.Y., Davids, K., Button, C., & Koh, M. (2008). Coordination changes in a discrete multi-articular action as a function of practice. *Acta Psychologica, 127*(1), 163–176. PubMed ID: 17555698 doi:10.1016/j.actpsy.2007.04.002

Didier, J.J., Li, L., & Magill, R.A. (2013). Environmental context affects outcome and kinematic changes at different rates during skill learning 1. *Perceptual and Motor Skills, 116*(3), 953–968. PubMed ID: 24175465 doi:10.2466/25.23.PMS.116.3.953-968

Hodges, N.J., Hayes, S., Horn, R.R., & Williams, A.M. (2005). Changes in coordination, control and outcome as a result of extended practice on a novel motor skill. *Ergonomics, 48*(11–14), 1672–1685. doi:10.1080/00140130500101312

Hong, S., & Newell, K. (2006). Change in the organization of degrees of freedom with learning. *Journal of Motor Behavior, 38*(2), 88–100. PubMed ID: 16531392 doi:10.3200/JMBR.38.2.88-100

Horak, F.B. (2010). Postural compensation for vestibular loss and implications for rehabilitation. *Restorative Neurology and Neuroscience, 28*(1), 57–68. PubMed ID: 20086283 doi:10.3233/RNN-2010-0515

Jaric, S., & Latash, M.L. (1999). Learning a pointing task with a kinematically redundant limb: Emerging synergies and patterns of final position variability. *Human Movement Science, 18*(6), 819–838. doi:10.1016/S0167-9457(99)00042-1

Kelso, J.A.S. (1995). *Dynamic patterns: The self-organization of brain and behavior*. Cambridge, MA: MIT Press.

Ko, Y.G., Challis, J.H., & Newell, K.M. (2003). Learning to coordinate redundant degrees of freedom in a dynamic balance task. *Human Movement Science, 22*(1), 47–66. PubMed ID: 12623180 doi:10.1016/S0167-9457(02)00177-X

Latash, M.L., & Turvey, M.T. (1996). *Dexterity and its development*. Mahwah, NJ: L. Erlbaum Associates.

Liberati, A., Altman, D.G., Tetzlaff, J., Mulrow, C., Gøtzsche, P.C., Ioannidis, J.P., . . . Moher, D. (2009). The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: Explanation and elaboration. *PLoS Medicine, 6*(7), e1000100. PubMed ID: 19621070 doi:10.1016/j.jclinepi.2009.06.006

Majed, L., Heugas, A.-M., Chamon, M., & Siegler, I. (2012). Learning an energy-demanding and biomechanically constrained motor skill, racewalking: movement reorganization and contribution of metabolic efficiency and sensory information. *Human Movement Science, 31*(6), 1598–1614. PubMed ID: 23131382 doi:10.1016/j.humov.2012.06.004

McDonald, P., van Emmerik, R., & Newell, K. (1989). The effects of practice on limb kinematics in a throwing task. *Journal of Motor Behavior, 21*(3), 245–264. PubMed ID: 15136263 doi:10.1080/00222895.1989.10735480

Moher, D., Liberati, A., Tetzlaff, J., & Altman, D.G. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *Annals of Internal Medicine, 151*(4), 264–269. PubMed ID: 19622511 doi:10.7326/0003-4819-151-4-200908180-00135

Newell, K.M., & Vaillancourt, D.E. (2001). Dimensional change in motor learning. *Human Movement Science, 20*(4), 695–715. doi:10.1016/S0167-9457(01)00073-2

Newell, K.M., & van Emmerik, R.E.A. (1989). The acquisition of coordination: Preliminary analysis of learning to write. *Human Movement Science, 8*(1), 17–32. doi:10.1016/0167-9457(89)90021-3

Smith, D.R., McCabe, D.R., & Wilkerson, J.D. (2001). An analysis of a discrete complex skill using Bernstein's stages of learning. *Perceptual and Motor Skills, 93*(1), 181–191. PubMed ID: 11693684

Sparrow, W.A., & Irizarry-Lopez, V. (1987). Mechanical efficiency and metabolic cost as measures of learning a novel gross motor task. *Journal of Motor Behavior, 19*(2), 240–264. PubMed ID: 14988061 doi:10.1080/00222895.1987.10735410

Temprado, J., Della-Grasta, M., Farrell, M., & Laurent, M. (1997). A novice-expert comparison of (intra-limb) coordination subserving the volleyball serve. *Human Movement Science, 16*(5), 653–676. doi:10.1016/S0167-9457(97)00014-6

Vereijken, B., van Emmerik, R.E., Whiting, H., & Newell, K.M. (1992). Free(z)ing degrees of freedom in skill acquisition. *Journal of Motor Behavior, 24*(1), 133–142. doi:10.1080/00222895.1992.9941608