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Empirical Investigations of Nonlinear Motor Learning

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Abstract: Skill acquisition can be conceived as a nonlinear, emergent process punctuated by sudden changes in skill capability and coordination dynamics stability. The rate of learning when expressed in terms of movement dynamics typically follows nonlinear trajectories interspersed throughout practice with trial-to-trial fluctuations. In this review we present recent empirical evidence examining both individual learners and also groups or teams of learners, which serve to further illuminate the nonlinear nature of skill acquisition. Innovative experimental designs, and sophisticated data collection / analysis tools are common features of this rapidly expanding body of literature. Finally, we present a number of practical implications for consideration within sport and physical activity pedagogy in the 21st century. The key role of physical educators is to design tasks and games that provide learners with opportunities to explore and find movement solutions within a set of specific constraints (especially task constraints).

Keywords: Coordination dynamics, variability, pedagogy, skill acquisition.

INTRODUCTION

Recent global trends such as decreasing levels of physical activity and general motor competency [1] place renewed significance on an informed understanding of human motor learning and development. Since the late 19th century, movement scientists have considered the question of how humans learn to control and coordinate their actions, for an overview see [2]. In this article we propose that skill acquisition should be conceived as a nonlinear, emergent process punctuated by sudden changes in skill capability and coordination dynamics stability. To justify this argument we present recent empirical evidence examining both individual learners and also groups or teams of learners, which serve to further illuminate the nonlinear nature of skill acquisition. Finally, we present a number of practical implications for consideration within sport and physical activity pedagogy in the 21st century.

HISTORICAL VIEWS OF THE SKILL ACQUISITION PROCESS

Motor skill acquisition has traditionally been described as the internal processes that bring about 'relatively permanent' changes in the learner's movement capabilities [3]. Historically researchers have tried to understand skill acquisition by examining the performance changes that accompany practice. For example, in early research efforts, Bryan and Harter [4] studied how learners' typing skills developed while practicing to send and translate Morse code. Over a period of 40 weeks, the telegraphers went through distinct phases of improvement and periods where performance levels plateaued. The inference from such performance curves was that learners initially construct simple elements of the skill, interspersed by periods of consolidation (i.e., development of automaticity) before they link individual parts of movements (in this case individual finger presses) into more integrated patterns of learned behaviour (linked sequences of finger presses typed as words).

Analyses of performance curves have led many researchers to develop mathematical models of the rate of learning [5]. The strongest empirical support has been offered for a generalised power function, prompting A. Newell and Rosenbloom [6] to conclude that "…There exists a ubiquitous quantitative law of practice. It appears to follow a power law." (pg. 2). As the logarithmic function of the power law presents a straight line it has been tempting to assume that learning itself is a linear, deterministic process. Lane [5] is more reticent and commented that while the general appearance of performance curves can be anticipated reliably, "the time course over which acquisition runs, and thus the curve parameters, is generally not predictable from prior knowledge of task characteristics." (pg. 125).

There is little debate that learning of complex skills appears to follow "stage–like" characteristics where a learner's progression at any one time can be broadly categorised as belonging to one of several developmental stages. Amongst others, Fitts [7], Anderson [8], and Newell [9] have each proposed 3-stage models in which behavioural characteristics and the internal changes associated with learning are argued to be qualitatively different at each stage. Whilst both conceptually and practically valuable, such stage-models are relatively silent on the extent to which progression through the stages is a smooth, linear and a continuous process.

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Humans acquire skill by consistently coordinating relevant body parts into functional synergies. Historically motor learning theories have tended to attribute the coordination and control of movement to an executive controlling mechanism residing in the Central Nervous System. For example, the information processing approach views the performer as a sort of human communications channel in which the relationship between changes in input signals and system output are linearly related. As noise is an inherent feature of every biological system [10] it has been presumed that an important job for the performer is to gradually eliminate or minimise noise (or movement variability) through practice and task experience. Hence, the magnitude of movement variability has been viewed as an important feature for assessing the quality of system control [11]. The role of repetitive practice is often conceived of as reducing the amount of movement pattern variability viewed as noise. Further compounding this viewpoint, the selection of movement models to investigate motor system functioning has been biased away from dynamic, multi-joint actions prevalent in sports because of the view that experimental rigor could be better maintained in laboratory studies of simple movements [12].

In the past, the motor learning literature has suffered from an overemphasis on the amount of change in performance outcomes without sufficient analysis of the dynamic properties of change in movement coordination [13]. Undoubtedly this criticism may be partly attributed to the lack of sophisticated measuring devices for examining movement coordination. Another important issue is that skill acquisition research has typically been conducted over short, intense practice periods, such as a number of days [14]. For obvious pragmatic reasons there are few examples in the research literature of motor learning experiments performed over longer periods of practice, as experienced in real life although for a classic exception, see [15]. Hence, conclusions drawn from such "snap-shot" studies are likely to be based on the transient effects of practice rather than the more enduring consequences of learning.

Indeed, certain features of performance curves (e.g., transient warm-up decrements, relatively permanent performance changes) indicates that the process of learning is composed of multiple time scales, the importance of which has been overlooked in the quest to produce ubiquitous mathematical models of learning [16]. For example, minor fluctuations within a practice session exist on a different, much shorter timescale to a change in coordination pattern achieved over many hours of practice. An important consequence of different time scales in learning lies in the appreciation of inter-individual differences in learning behaviour. Investigating typical performance curves, Newell and colleagues [17] showed how the power-law of learning can be a mere consequence of averaging group data emphasising the application of intra-individual analysis methods, see also [18]. In the following sub-section we discuss the theoretical underpinnings of a constraints-led account of learning which has prompted us to look more closely at coordination dynamics during learning. According to Newell [19], constraints may be relatively time dependent or time independent. For example, the position of a cyclist's centre of gravity may fluctuate considerably during a practice session (time dependent) however the influence of gravity remains constant (time independent). That is, "the rate with which constraints may change over time varies considerably with the level of analysis and parameter under consideration" (pp. 347).

REDEFINING LEARNING AS A NONLINEAR, EMERGENT PROCESS

How do long term changes to the organisation of human movement occur as a result of learning and practice? From a constraints-led perspective, skill acquisition has recently been reconceptualised as a learner (a dynamical movement system) searching for stable and functional states of coordination or 'attractors' during goal-directed activity [2, 20, 21]. Stages of learning can be viewed as the creation of temporary states of coordination that resist constraints that could perturb the system's stability. For skilled performance, individuals eventually need to develop a repertoire of movement attractors to satisfy the constraints of changing contexts. We can consider this repertoire of attractors as a kind of perceptual-motor landscape to denote that performers need to learn how to coordinate their actions with their environment in order to perform skills effectively [22].

The perceptual-motor landscape is a useful metaphor for describing an individual learner's coordination dynamics. Its layout is constrained by genetic endowment, developmental status, past learning experiences and the task requirements. That is, each landscape is continually being shaped and altered by the interaction of an individual's genes, perceptions, and intentions, as well as physical constraints, surrounding information, and system dynamics [23]. Because these performance constraints are not static and fixed, the landscape is undulating, ever changing and hence emergent. As a learner's constraints change over time, the topology of the landscape alters to reflect the flow of information and of new experiences.

The landscape concept captures some of Bernstein's early observations about the evolution of coordinative structures in learning. Bernstein [24] proposed that coordination involves the mastery of redundant degrees of freedom in order to perform an action. He suggested that in motor learning, initial practice results in freezing of degrees of freedom to eliminate any redundancy which are subsequently released with practice as degrees of freedom are organised into a coordinated movement unit. Anderson and Sidaway's [25] soccer kicking study subsequently provided empirical support for Bernstein's ideas. They showed that learners placed constraints on their joint range of motion (ROM) at the hip and knee initially. With practice, these constraints were relaxed and the hip and knee joints typically had greater freedom of movement which enabled the kicking leg to take greater advantage of the velocity generated at the hip. As practice proceeds, less successful patterns are believed to be gradually sacrificed by the learner and more successful actions are reinforced by strengthening connections between intentions and energy flows.

Localised within a region of the landscape, the performer may find several areas where successful solutions are closely situated; these regions are solution manifolds [13]. Within solution manifolds small fluctuations alter the task-solution only minimally, providing some sort of task tolerance. Large solution manifolds have more tolerance for different movement solutions, where smaller manifolds may only allow subtle modifications. For example, a penalty kick in soccer which can be achieved successfully in a number of different ways has a relatively large solution manifold, however the basketball free throw shot which seems to have less tolerance for variation [26] has a small solution manifold. Movement variability during learning allows the learner to search, find and subsequently refine appropriate solution manifolds for different performance contexts [13]. Influential constraints such as task goals, exploration, intrinsic dynamics and feedback stabilise certain areas of the landscape allowing the learner to experiment until effective movement solutions are found. Consequently the rate of learning when expressed in terms of movement dynamics typically follows nonlinear trajectories (e.g., an exponential function) interspersed throughout practice with trial-to-trial fluctuations [18].

Hence, motor learning is a process that occurs over several timescales (i.e., moment to moment, trial by trial, practice session by session, year by year, etc.) meaning that parameter change can be sudden and substantial, as well as gradual and incremental. The landscape analogy also evokes the idea that learning is not unidimensional and that performance levels may fluctuate considerably on the way to achieving the long term goal of stable, consistently high outcomes. It is when performance and movement coordination are analysed at multiple levels that the (essential) nonlinearity of this process is most obvious. In the next section we discuss recent research that describes how constraints influence nonlinear learning from an individual and group perspective. These empirical studies typically adopt multiple levels of analysis, indicating that much of the traditional research on motor learning may have neglected essential components of the learning process.

EMPIRICAL ANALYSIS OF INDIVIDUAL LEARNING

Motor learning can be examined at both individual as well as group or team levels. To date, most motor learning research has focussed on the individual level although increasingly social networks of learners are now coming under scrutiny [27]. As discussed above, skill acquisition at an individual level has traditionally been characterised by a gradual increase in performance scores or improvement in timing in terms of performing a learned task [13]. Motor learning studies, from a dynamical systems perspective, look at individual changes over time. Patterns of movement coordination within individuals are studied using tools such as cluster analysis or principal component analysis (PCA) [28, 29] and through the study of variation in individual performance scores or timing throughout learning sessions [30, 31].

Newell, Liu and Mayer-Kress [16] interpreted learning as a progression in time on an attractor landscape toward a fixed point. In other words, movement performance will tend to approach a stable state with practice. For example, Chen and colleagues [30] applied a modified 'Cauchy theorem' which consisted of a movement pattern difference score to measure the convergence of a behaviour towards a fixed point as an indication of learning. In this study, skill level of an upright pedalo-locomotor task was determined by temporal criteria (i.e., shorter movement time and improved movement smoothness) as well as spatial variables (i.e., increased consistency of movement patterns). Although learners revealed fluctuations throughout the practice trials, movement pattern variability reduced significantly over time (i.e. increased in consistency in a nonlinear fashion) which were consistent with the expectations proposed by Newell and colleagues [16]. Thus, the authors suggested that the consistency measure appears to be a useful method for examining changes in multiple degrees-of-freedom over time and the learning of whole body actions such as high board diving and gymnastics. In addition, the findings showed that while movement time had plateaued at the end of the practice session, the participants were still searching for the dynamical stable fixed point in terms of movement dynamics (movement pattern difference score). This provides support. That traditional motor learning studies which rely solely on performance scores as an indication of success may have ignored important components of the learning process.

Nonlinear dynamical systems do not follow continuous linear progressions but rather display sudden, rapid changes in behaviour [2, 32]. Learning a 90° relative phase bimanual finger flexion-extension task, determined by a "visual metronome", resulted in a change in attractor states towards the newly learned coordination pattern which persisted for one week after practice [21]. In addition, phase transitions from bistable-to-multistable, or multistable-to-monostable dynamic patterns, were sometimes accompanied by a loss in stability of intrinsic patterns [21]. A subsequent study highlighted that pre-existing individual differences resulted in different learning strategies [33]. Liu and colleagues [34] showed similar observations in a rollerball task. Eight participants were assigned to either a 42-rps or 35-rps initial ball speed group and practiced for 45 trials a day, over 3 possible practice days. If the participant was successful in learning the task, then the practice session was completed. The task was considered "successfully learned" when the participant performed eight 30-s trials above a threshold speed out of 10 consecutive trials. Individual analysis showed that participants were subcategorised into those that produced: a) a transition to successful performance (2 participants from 42-rps condition), b) a scaled-up performance without transition to successful performance (2 participants from 35-rps condition and 1 participant from 42-rps condition) and c) no improvement in performance (2 participants from 35-rps condition and 1 participant from 42-rps condition). The two participants who achieved success displayed an increase in ball acceleration fluctuation before success (i.e., switching to a new coordination mode). The group which showed improved ball acceleration but did not achieve success (category b) displayed several occasions of increased variability. The sudden, abrupt nature of transitions in this study were described by the authors as: "consistent with a saddle-node bifurcation or nonequilibrium phase transition" (pg. 392). Variability increments observed in categories (a) and (b) were described as epochs of explorative behaviour which were not observed in the group (category c) without any improvement in performance [34].

In recent times, kinematic case studies of learners practicing multi-articular actions have begun to appear in the literature. For example, in Chow *et al.*'s study [28] 4 novices practiced kicking a soccer ball over a barrier to a live receiver for 4 weeks. Cluster analysis of intra-individual kinematic variables showed that all participants, except one, demonstrated a change in preferred movement patterns following practice. This refers to a change in the individual kicking patterns represented by a change in movement clusters (see Fig. **1**). Movement clusters were determined in a hierarchical grouping process by the differences between various types of kinematic variables (e.g., hip, knee, and ankle joint range of motion) for both kicking and non-kicking limbs. Variability, indicated by the number of cluster of movements exhibited within a session, only preceded a defined change for two of the participants. Participant YH, as shown in Fig. (**1**), illustrated a change from a preferred cluster (C1) in session 1 to four different movement clusters (C1, C2, C3, C4) in session 2, and a new preferred pattern (C6) in session 4 followed by an increase variability from session 5 to 6 and finally a new preferred pattern (C2) from session 7 to the end of the practice sessions. Fig. (**2**) displays the hip and knee joint angles for the kicking trials of participant YH, illustrating the two main clusters (C1 and C2) present during the practice sessions. Participant KL demonstrated occasions of high variability in movement clusters without a change in preferred movement clusters in following practice sessions. In addition, a lack in variability of movement clusters was also observed for the other two participants who displayed a smaller rate in improvement from pre to post test, similar to the findings in Liu *et al* [34]. Overall it was interesting to note in several participants, that a sudden change between movement clusters did not necessarily precede an immediate improvement in performance and that often a period of parameterising (refining) the new pattern was necessary before performance improved. This study illustrates that whilst movement variability can predict changes between preferred patterns, it may not always signal such changes and it may be indicative of other performance related factors.

Perhaps surprisingly, there has been limited empirical evidence to support Bernstein's early observations about coordinative structures (i.e., that humans initially constrain and gradually free motor synergies). Furthermore, researchers have questioned if Bernstein was referring to dynamical degrees of freedom (collective spatial and temporal organization of joints and body segments) or mechanical degrees of freedom (motions of individual joint angles) in his seminal writings. Hodges and colleagues [35] investigated the changes in movement kinematics and accuracy as a function of 9 days of soccer-chipping practice with the left foot for a 26-year old novice. In this case study, radial error decreased (i.e. improvement in outcome scores) over practice while the most significant changes occurred at the hip for the move-

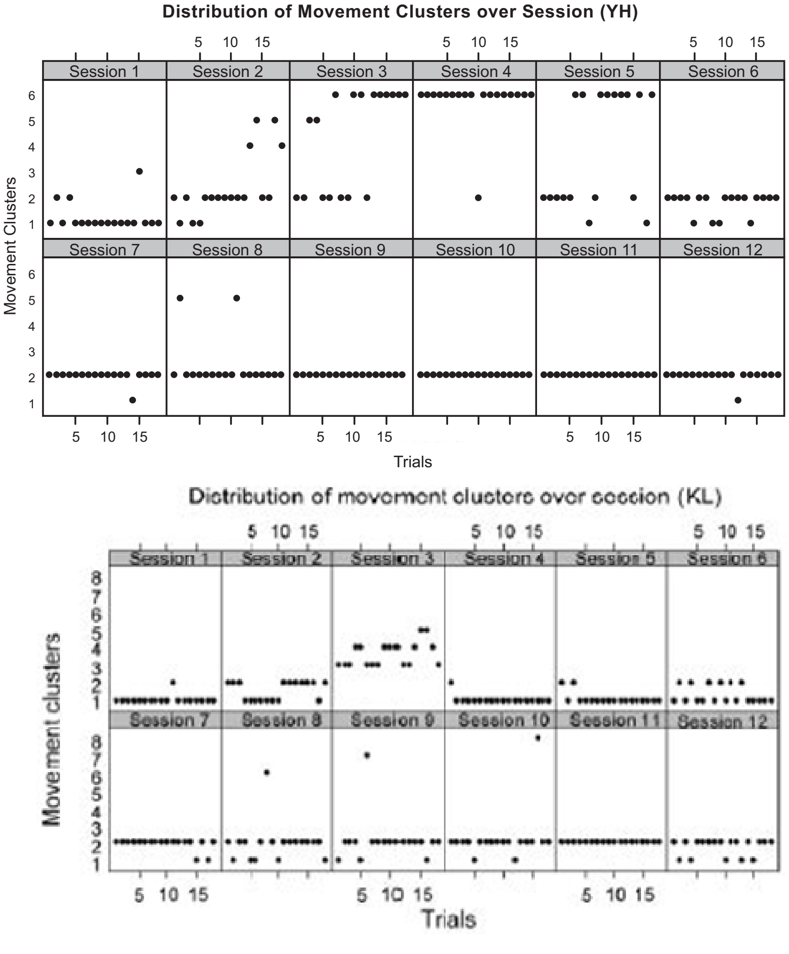

Fig. (1). Distribution of movement clusters over practice sessions for all participants. Number of trials per session is shown on the x axis. Movement clusters for all sessoins are shown on the y axis. Reproduced from Chow *et al*. (2008) with permission of Human Kinetics.

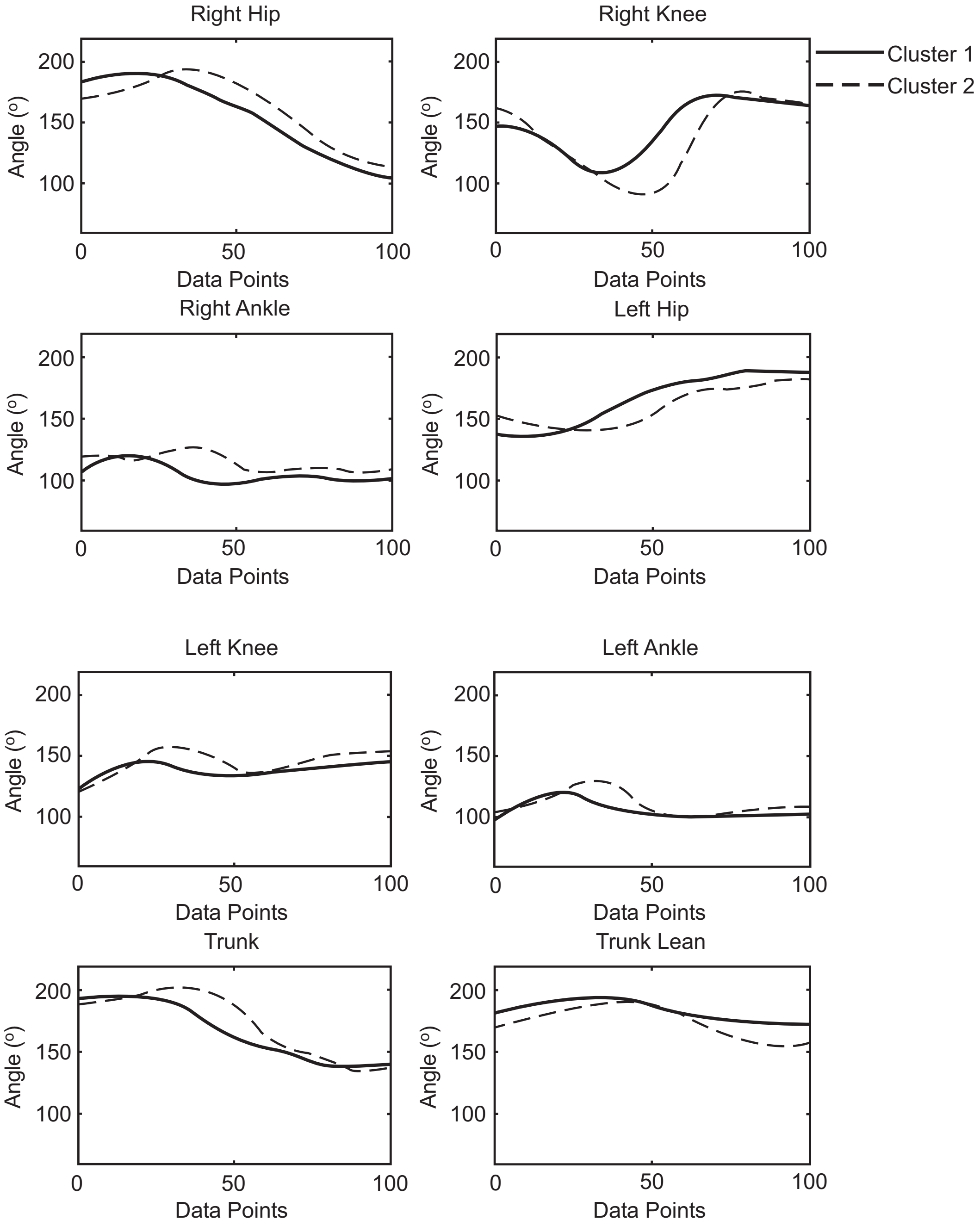
Right Hip
Right Knee
Right Ankle
Left Hip
Left Knee
Left Ankle
Trunk
Trunk Lean

Fig. (2). Joint angles from the kicking (right) and non-kicking (left) legs of Participant YH. Reproduced from Chow *et al*. (2008) with permission of Human Kinetics.

ment kinematics. In particular, the range of motion (ROM) of the hip decreased from day 1 to 5 of practice and then started to increase after the first session on day 5 until the end of practice (see Fig. **3**). In addition, the ROM results in Hodges's study were also supported by the linear coupling between joints (cross-correlation coefficient data) whereby the degrees of freedom moved from freeing to freezing and then back to freeing throughout practice. Hodges and colleagues [35] suggested that the initial freezing of degrees of freedom was a temporary strategy used by learners to assist performance and that with extended practice, task demands are achieved more consistently and effectively by independent joint control (and potentially more complex synergies).

Not surprisingly, the nature of the task being learnt appears to have a significant role in shaping how dynamical degrees of freedom are regulated. The ski-simulator has proved a useful device to study the dynamics of learning over the years [36]. For example, in one study, seven days of practice on a simulator resulted in the suppression of mechanical degrees of freedom followed by the stabilization of the new pattern of coordination whereas there was no change in the number of dynamical degrees of freedom as a function of practice [37]. Similarly, learning to play a violin was not associated with the release of degrees of freedom. Instead, greater practice experience was associated with a decrease in shoulder ROM and a reduction in bow-movement variability

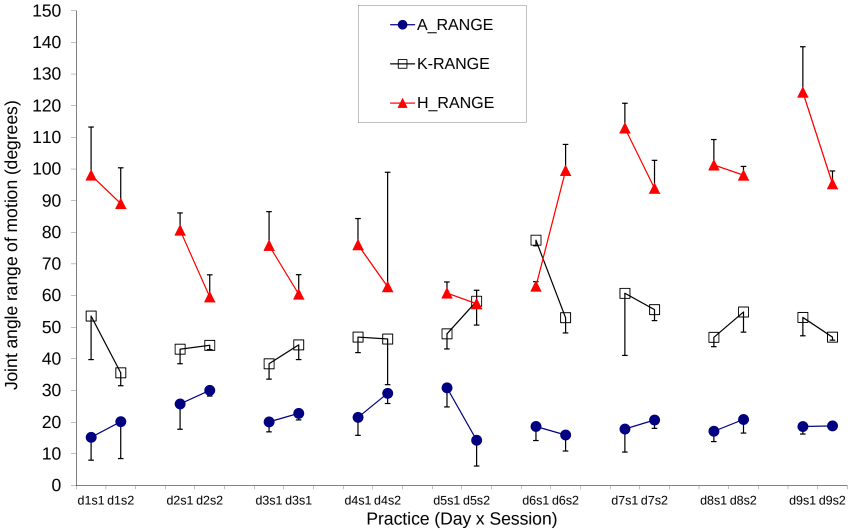

Fig. (3). Range of motion and SD bars (degrees) for the hip, knee and ankle as a function of practice day and session. Reproduced from Hodges *et al*. (2005) with permission of Taylor & Francis.

[38]. The authors pointed out that the strategies used to constrain mechanical degrees of freedom for learning a skill is task-specific, rather than age-dependent. In particular, the findings suggest that restricting joint amplitude at selected joints while leaving other degrees of freedom unconstrained is an appropriated strategy for learning complex, high-precision motor patterns for both children and adult learners [38]. Collectively these results verified that the mastery of degrees of freedom seems to be noticeably more complex and task dependent than has been implied from Bernstein's seminal writings.

In summary, this section provides evidence to support the importance of individual analysis from a nonlinear dynamics' perspective. For example, several studies which examined joint ROM during practice showed that mastery of degrees of freedom by learners is both a complex and task-specific process. In addition to examining degrees of freedom in coordinated movements, the dynamic attractor landscape has been used to study changes in attractor states and stability of the system following a learned task. From a nonlinear, constraints-led perspective, movement variability is often necessary for learning to occur while increased stability of a novel coordinated pattern is an indication of learning. Finally, several of these studies have highlighted that learning rates as well as learning strategies vary between individuals [30, 31].

EMPIRICAL ANALYSIS OF TEAM LEARNING

Arguably the focus on quantifying the global aspects of team learning has been limited by the inherent complexity of group behaviour such as in team sports. Especially in team sports such as soccer and hockey where low scores and continuous ball flow does not reliably measure the players collective skill level using linear statistical tools [39]. This is where nonlinear analysis can quantify the skill level in a team setting. It has been suggested that team work can enhance greater creativity than individual activity [40]. However, it is still difficult to determine what factors are pivotal for learning as a coherent group under the given constraints such as size of team, playing area dimensions, time allocation of game play. Past researchers in team sports have quantified individual and dyadic performance or small sided games to investigate team behaviour and it is these studies that we shall consider in this sub-section.

Collective behaviour in team sports cannot be understood by simply quantifying individual performance parameters such as total running distance, running velocity, geometric shape, common centre of gravity and so on [41]. This is primarily because organismic constraints (varied anthropometric measurements) and task constraints (e.g., numbers of players, typical team sports are invasive whereas individual sports are combative) differ considerably in team sports. A team sport is not simply a culmination of individual skills [42]. The overall movement of a team is dynamically interrelated. Expert team players not only have more refined motor skills but also possess increased tactical awareness that allows them to focus on complex game features such as opponent's skills and limits [43].

Researchers in sports performance have defined skillfulness by acknowledging the contributions of both motor control and game knowledge [44]. A review article by Turner *et al*. [45] illustrates that invasive games constitute tactical understanding for skillful performance. Typical invasive games require players to cope with dynamic environment demands such as changing team formations. To attain peak performance, individual players must be competent to make quick selective decisions and adapt their motor control according to the evolving environment. Game play can evolve when the state of balance ruptures suddenly [46]. Thus players have to anticipate the course of game play and cannot be confident on a pre-determined plan i.e. strategy.

Network analysis has been the favoured tool among researchers investigating the inter-relation between agents in social networks [47]. Recently a social network based study was conducted to understand the contribution of individual soccer players to the overall team performance [48]. The study highlighted the influence of certain players by constructing a network based on the ball flow between two players. The 'flow centrality' is the normalised distribution of player performance (minimum of five successful passes), that results in a shot. In a tentative estimate it is acceptable that the player performance can be extended to the team level by calculating the average performance of a subset of players. However, in this study 'successful pass' was the only parameter considered to determine individual performance in a team game. Other factors such as player's skill, knowledge, specificity of task would also be important to objectively quantify in future work to determine the collective contribution of players in a team game [43].

Coordinate profiling of players has also been a popular tool to define the structure of a team under varying constraints. A study investigated the variation of tactical behaviour in youth football teams and small-sided game conditions [41]. The spatio-temporal variables included total running distance, running velocity, team shape and geometrical centre difference, whereas the constraints included number of players (organismic) and pitch dimension (environmental). All these factors were incorporated to find a collective team variable (*lpw_ratio*), which looked at the changing shapes of the area enclosed by the players in various sub-phases of the game such as attack and defense game play. *Lpw_ratio* is a collective variable, which is the based on the ratio between length and the width of the players occupying the pitch space. *Lpw_ratio,* being a non-dimensional unit, has an advantage as a performance indicator, owing to the fact it is independent of any unit and favours comparative analysis [49]. There was a decrease in *lpw_ratio* with increase in age group, suggesting that the youngest players tend to solve game tasks by trying to be closer to the ball and using individual executions, rather than a collective approach [41]. In team sports context this phenomena can be visualised as a form of "swarming behaviour" common in children's football [50]. However, just quantifying pitch occupancy using quantitative measures at different age groups will not highlight what factors led to the changing state space. Instead, it would be interesting for future research to conduct questionnaires' with individual players based on team game aptitude (qualitative) and simultaneously investigate spatio-temporal characteristics of players (quantitative). The introduction of questionnaires will supposedly reflect the factors which are unique to the decision making process in the context of the game. This approach might be used to correlate the game-specific knowledge of a team with actual game play.

Behavioural scientists have investigated the interpersonal dynamics (decision making and attacking) in dyadic movement of rugby union players [27]. A collective variable (vector connecting the dyads) was identified, which was later processed using different nonlinear tools such as:

1. First derivative analysis (analyse the rate of change of the relative positioning between an attacker and defender).
2. Phase space plot (investigate the nonlinear variability and periodicity in dyads).
3. Approximate entropy (quantify the predictability of the dyadic movements in the collected time series).

The study highlighted the evolving nature of game play, i.e. the behaviour of team players exhibited emergent and self-organising characteristics. Although this investigation garnered strong evidence to link dynamical systems theory (DST) to sub-phases of rugby, i.e. team sports, it would be beneficial to study what factors led to the decision-making process in the game situation. Future research in team sports pedagogy might in turn incorporate the critical factors of decision making in team game learning.

Whilst to date, there is limited research on team (or collective) learning, it is apparent that like individual learning, the process is characterised by nonlinear phenomena (such as emergence, dynamic inter-relations, multistability and phase transitions). It seems that future research will need to adopt innovative, multidisciplinary methods to analyse collective learning. Team sports are inherently complex and therefore the tools of nonlinear dynamical systems theory seem well placed to improve our understanding of learning in these common situations. Findings from these empirical investigations on nonlinear motor learning suggest that teaching and learning in practical settings should encompass strategies that stem from nonlinear dynamics.

PRACTICAL IMPLICATIONS

As discussed previously, physical educators need to (re)consider the 'traditional' practice of planning and implementing repetitive drills which include repeating a movement continually during practice to get players consistent. These drills are often too static and place limited emphasis upon how the skill might be functionally adapted for performance in dynamic real game situations. Instead, physical educators should consider designing and modifying practice tasks and games that maintain the functional information-movement couplings of the practice tasks or games. This allows a learner to increasingly couple the information available in the learning environment to the actions needed to achieve a specific task goal as practice proceeds. For example, learners should be given opportunity to be involved in real game practices. The presence of real game context (particularly in small-sided games) allows critical information-movement couplings to be maintained when learners execute movement in response to the perceptual information that is continuously available in the practice setting.

In typical invasion games, players can learn to adjust to the dynamic environmental demands such as changing team formations and be able to make quick selective decisions and adapt their motor control according to the evolving environment. As noted by Grehaigne *et al.* [42] team sports are not simply a culmination of individual skills; or put differently the whole is greater than the sum of its parts. As such, games and practice task constraints should mimic the actual performance environments as much as possible.

Closely related to the idea of information-movement couplings, the infusion of variability in modified games and practice tasks is critical for the learner to explore a larger performance 'solution space', thus enhancing a learner's flexibility and adaptability. Thus, although learners may show fluctuations as games and practice proceed, movement variability should not necessarily be seen as a sign of inconsistency and therefore detrimental to movement performance outcomes. Instead, physical educators need to understand and view movement variability as an integral process in learning and acquiring effective movement patterns specific to a task goal. Although coaches implement various orthodox training drills, which tend to simulate practice sessions with real game scenarios, they need to realise that movement variability will reduce over time as movement patterns develop stability and more successful actions will be reinforced. The resulting movement performance outcomes will be more relevant and effective in providing the flexibility required to adapt to complex dynamic sport environment [2].

Thus, the key role of physical educators is to design tasks and games that provide learners with opportunities to explore and find movement solutions within a set of specific constraints (especially task constraints). This, however, does not simply mean allowing 'freeplay' during lessons. Instead it requires physical educators to carefully manipulate task constraints appropriate to guide learners in adapting their movements to overcome specific movement challenges in modified games. For example, in a 3 vs. 1 throw-catch possession game, having a rule that disallows the use of high passes (e.g. ball cannot be thrown above head level), physical educators can challenge learners to adapt their throwing movements to passes such as the bounce or chest pass and moving in front of defenders for a clear channel to receive a bounce or chest pass rather than a lob.

As discussed earlier, practitioners should also plan for realistic game-oriented scenarios, in which learners participate in more dynamic modified game play and avoid overloading learners with all the technical constraints of the game (skills and rules) during the early stages of learning. Game-oriented scenarios allow educators to tactically reinforce the environmental constraints (e.g., positional play) and task constraints (e.g., rules of the game). This idea is congruent with in the pedagogical strategy Teaching Games for Understanding (TGfU) [51]. As Hopper stated, "skill learning is not for playing games; rather playing games is for skill learning" [52]. Hence, practitioners can prioritise learning of game tactics rather than specific technical skills; the latter can be developed when the learner shows signs of attuned game perception [53]. Lessons on refining skills in a later stage enable systematic progression from a fundamental movement pattern to an advanced movement pattern [54].

Additionally, Hopper [52] noted that tactical skills need to be taught initially through modified game plays to make the skills more purposeful. For example, an amateur learner has to sprint forward to intercept a ball or kick the ball in a certain direction to make an advantageous pass. The learner then realises that in order to have a better scoring opportunity, he/she might have to replace the fundamental skills (linear sprinting) with a further refined skill (dribbling or dodging) under the guided supervision of educators. Thus, the learner can transiently improve his/her performance in the team.

Physical educators also need to understand the different time scales in learning; different learners may progress at different rates in acquiring game tactical knowledge/technical skills. For example, matching task difficulty to the learner's skill level has been suggested to facilitate learning effectiveness [55]. In an attempt to verify this, Choi *et al* [55] introduced a multiple task motor program that included practice schedules that were adaptive both in difficulty and in number of trials for each task. This study showed that performance-based adaptive scheduling produced better results than random scheduling on a delayed retention test, providing evidence that motor learning is enhanced when the task provided or instructions given complements the individual learning needs. Hence, physical educators need to adjust the complexity of the learning task appropriately to adequately challenge learners to achieve success. This can be done by manipulating the task constraints. Useful constraints such as changes to space, target areas, equipment, player numbers involved, goal of the task, and rules of the activity can be added to small-sided games. For example, in a modified 4 vs. 4 soccer game, the educator could increase the task difficulty for attackers by placing a time limit for attackers to score a goal. In a mini, simplified 3 vs. 3 volleyball game, the educator may allow lower skill learners to have an additional bounce between volley passes by the same team.

Using the nonlinear approach in learning also requires some reconsideration of assessment. Traditionally, practitioners have adopted skill battery tests to evaluate a learner's ability to execute a sports skill. While skill battery tests can be a good measure to examine the skill in individual settings, it is unrealistic and limited when transferred to game play [56]. For assessment in game play, practitioners may consider the Tactical Decision-making Competency (TDC) model proposed by Pagnano-Richardson & Henninger [57]. The TDC model, developed to assess students' focus of attention during game play, consists of four levels of competency; they are self and skill execution; self and teammates; self, teammates, and opponents; and self, teammates, opponents, and situation. The model proposed that students' focus during game play progresses across these four levels of competency, starting from themselves and their skills, and eventually to the game situation (e.g., considering opponents' formation) as they become more competent in game play [57].

However, assessing students' TDC in game play in PE can be challenging since physical educators are unable to observe students' thoughts during game play. Pagnano-Richardson and Henninger [57] suggest using assessment records of students' TDC based on four teaching techniques. These are: 'Simply Ask" (e.g., asking students to verbally respond to questions on their thoughts during game play), posters (e.g., displaying four posters, each representing one level of TDC and getting students to stand under the poster that best represents their thoughts during game play), journal prompts (e.g., developing questions to assess students' TDC through their journal entries), and exit cards (e.g., getting students to respond to a variety of questions on index-size cards and collected as they leave the class). These techniques not only allow students to identify their decision-making during game play, but also allow physical educators to assess students' progress across the levels of TDC [57].

In conclusion, recent empirical investigations of motor learning support the viewpoint that learning is a nonlinear, dynamical process. More specifically, skill acquisition is conceived as an emergent process punctuated by sudden changes in skill capability and coordination dynamic stability (2). As the learner/s searches for stable and functional states of coordination during goal-directed activity [58], the learner/s may display an increase in variability by a large fluctuation in performance or coordination before a successful movement pattern is learned. Movement variability during learning allows the learner/s to search, find, and subsequently refine appropriate solution manifolds for different performance contexts [13]. These ideas raised in this paper have several practical implications for consideration within sport and physical activity pedagogy; they could inform practitioners to more effectively engage learners using the nonlinear approach to learning [59]. Further research is needed to identify the different, nested timescales across which the learning process evolves. Also the inclusion of both discrete and continuous tasks in empirical work is necessary before the approach that has been described can form a global and pervasiveness theory of learning.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

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