Selected aspects of Nikolai Bernstein's theory assessed with modern motion analysis tools

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Abstract

Nikolai Bernstein was a forerunner of the systemic concept of human movement control, who had an overwhelming influence on authors of modern ideas of motor control and motor learning. The purpose of this scientific essay is general knowledge about the importance of neuro-physiological conditioning using new technologies of movement pattern analysis against the background of Bernstein's theory. Three issues were subjected to heuristic evaluation: reduction of degrees of freedom, timing, and anticipation. The study group comprised novice and advanced athletes of various sports. A novice-expert paradigm was used to determine the variability and quality of acquired movement patterns in the athletes. The following testing procedures were reviewed: surface EMG, ground reaction force plates, eye tracking, and motion capture systems. The findings confirm the key role of timing, anticipation, and reduction of degrees of freedom in the motor learning process. Practical implications were formulated, and significant importance was assigned to contextual interference, overlearning training, and trial-and-error method as well as perceptual training in reducing the processing time and improving motor learning efficiency.

Keywords: anticipation • degrees of freedom • electromyography • motor learning • movement patterns timing

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Motor neuron, motor neurone – *noun* a neuron that is part of a nerve pathway transmitting impulses from the brain to a muscle or gland [37].

The cortico-basal ganglia--thalamo-cortical loop (**CBGTC loop**) – m is a system of neural circuits in the brain. The loop involves connections between the cortex, the basal ganglia, the thalamus, and back to the cortex [38].

Technique – *noun* a way of performing an action [37].

Tactics – *plural noun* the art of finding and implementing means to achieve immediate or short-term aims [37].

Mae geri – 'front kick'," is the most basic of the many kicks in Shotokan karate.

INTRODUCTION

The modern pioneers of neurophysiology are considered to be Charles Scott Sherrington (1924) [1] and Nikolai Bernstein (1967) [2], who developed their respective concepts in the first half of the 20th century. The former described the mechanisms of brain function, muscle innervation, and the nature of synapses and receptors. For these accomplishments he was awarded the Nobel Prize in Physiology or Medicine. Nikolai Bernstein developed the movement control theory from an evolutionary perspective. The essence of Bernstein's original concept was the systemic relationship between the structure of the nervous system and construction of purposeful motor activities, which paved the way for new fields of knowledge such as motor control (control and regulation of human motor activities) and motor learning. The outcome of this concept was a hierarchical 'brain skyscraper' five-level model of mental-motor abilities [3].

In the model the A-level is responsible for and controls muscle tone, necessary for postural balance and generation of biological energy to ensure movement. Muscle synergies are controlled from the B-level, enabling co-activation of the flexors and extensors of individual joints. In conjunction with the higher levels, the synergies determine coordinated actions of the entire neuromuscular system. The C-level has been termed the 'space field level' responsible for, e.g. the temporal structure of sensory-motor responses. It is divided into two sublevels: the C1-sublevel associated with the striatum; and the C2-sublevel with the cerebral cortex. The D and E-levels are all-cortical, detached from environmental stimulation. All processes at these levels have explicitly psychological associations. The A, B, and C-levels operate mainly from the spinal cord, controlling ongoing motor activities in response to environmental stimuli. In contrast, the D-level operates far more slowly and is involved in the development of new movement patterns and the modification of previously acquired ones for future use, based on temporal and spatial anticipation. On the basis of neurophysiological analyses, the highest, cortical, E-level is associated with consciousness, motor imagination, and motivational and emotional factors of movement control in a changing environment.

In the hierarchical movement control system, a higher level of the central nervous system should not control the entire movement process specifically. The system controls movements so to speak 'in general' while making relevant corrections on an ongoing basis [4]. As Czajkowski [5] indicates, well-learned motor habits take the form of movement patterns, controlled independently from the spinal cord level. From the point of view of technique improvement in sports based on open motor habits, the cortical level provides strategic and tactical thinking, while technical operations occur in a state of secondary consciousness at the A, B, and C levels.

One of the main paradigms of the above-discussed theory is the concept of reducing degrees of freedom in the process of learning complex motor activities. It involves the gradual elimination of previously learned but unhelpful habits in the course of learning a new motor activity so as to deliberately create a new, technically complex, and correct sensorimotor action.

In practical terms this idea was extended into a way of learning movements called by Bernstein the "repetition without repetition" method, which found much wider applications, for example, in robotics and prosthetics. A reverse analogy to the operation of machines that always perform the same movements in the same way can serves as an illustration here. The sequence of machine actions involves a strictly programmed number of degrees of freedom, whose trajectories are determined by mechanical joints. In the event of changes in circumstances, machines have no alternatives; they are, as it were, helpless. The advantage of human beings lies in the fact that the goal of a movement task can be achieved differently, faster, and more rationally. This rationale yields the idea of contextual interference effect in motor learning popularized by [6], the essence of which is the discontinuation of inefficient learning of motor activities in blocked order and in fixed conditions in favour of variability of practice in random order [7]. This neural-psychic mechanism enables a more secure, permanent, and, at the same time, flexible memorization of movement patterns in the memory structures of the central nervous system. Moreover, in cases of combined motor habits in sports technique, it promotes the efficiency of performance in states of high arousal, e.g. in competitive sports.

Another issue related to Bernstein's concept is timing, i.e., the changing time frame characterizing all motor activities in the process of their improvement. Using the above-described five-level model, timing is controlled from the C2 sublevel, and thus above the capabilities of the subcortical nuclei in the zone of influence of cortical centres, and even from the D-level [8].

Based on Bernstein's system, a number of different concepts of motor control have been developed, the most useful of which are theories of dynamic systems within complex neurobiological systems [9-11], described from an ecological standpoint and emphasizing the interactions between the human body and the environment. Another trend comprises Richard Schmidt's [12] ideas of motor control, presented in his seminal work *Motor Control and Learning* developed on psychological grounds including neurophysiologically conditioned motor behaviours. It is significant that in the introduction to his book Schmidt included notes with photographs of Sherrington and Bernstein, which can be seen as reflections of the impact of their views on Schmidt's findings in the area of motor control.

One of the main hallmarks of Schmidt's concept is the psychomotor response pattern based on motor programs, intrinsic and extrinsic feedback, and the reaction time (RT) paradigm using EMG. In addition, Schmidt emphasizes the importance of the fore period and premotor time within RT in complex sensorimotor responses. He attributes an essential role to the hypothetical course of the EMG curve during the various phases of motor activity. This approach highlights the essence of neuromuscular control from the motor cortex and its reflection at the level of effectors, i.e. a muscle activation structure defined by the EMG signal.

Using the main premises of Bernstein's system, the aim of this study was to discuss three aspects: reduction of degrees of freedom, timing, and anticipation in the light of current research with the aid of modern technologies, and to formulate practical implications.

When analysing motor activities and their control, it is rather difficult to proceed without surface electromyography (sEMG) – a key tool allowing multi-channel recording of bioelectric tension of muscle activity, in cooperation with motion capture systems or ground reaction force plates. However, the flow of stimuli at the neuronal level depends on biochemical factors such as protein activity at synaptic junctions and the sodium-potassium pump. It is the bioelectrical tension induced by the polarization and depolarization of the nerve membrane of axons and dendrites that affects the EMG values of muscles innervated by the relevant moto neurons.

The reduction of degrees of freedom has been the subject of many publications, mainly from the motor learning perspective. Authors emphasize the application of new learning methodology, e.g., the trial-and-error method recommended by Bernstein himself. A somewhat more modest contribution can be observed in laboratory research including pedagogical experiments. A useful research method has been also the novice-expert paradigm, which allows for the description of model characteristics of movement patterns following a long-term learning process [13]. The use of EMG in studies of the quality of movement patterns – mainly movement structure and timing of activation of individual muscles and muscle groups in terms of their co-activation (agonists and antagonists) – has made it possible to qualitatively assess the development of complex movement structures.

The question of timing, i.e. the time frame that defines each motor activity, is an integral part of any analysis of movement patterns from the perspective of both motor control and biomechanics. Reaction time (RT) and movement time (MT) belong to different 'brain skyscraper' levels of the central nervous system, with the former associated with the cortical centres in decision-making processes. The centres responsible for stimulus perception and identification play an important role here. Studies have shown that a reduction in RT (the interval from stimulus onset to the first EMG activity) always affects the motor phase (MT), resulting in better efficiency (reduced time) of the whole of sensorimotor responses. Results of research on simple and complex sensorimotor responses, including choice reactions, have proven to be extremely relevant. Although studies of simple responses revealed no significant differences considering novice and expert athletes, the results of complex responses gave unambiguous primacy to the latter. The interpretation of this phenomenon has two implications: one stemming from genetic reasons, i.e. simple reactions are not very trainable; and the other related to experience, i.e. the effects of the training process. As shown by studies of martial arts practitioners (karate, taekwondo, fencing) outstanding athletes were able to reduce their reaction times in complex tasks to the levels similar to those in simple reaction tests on novices.

Temporal and spatial anticipation plays also plays a significant role in the training of sensorimotor responses in sports. According to experts, 80-90% of competitive responses in sports based on open motor habits are anticipatory in nature [14]. A notable illustration of this is provided by [15] in his metaphor of a fox that successfully hunts a hare dodging zigzags, heading in a straight line anticipating the movements of its prey. Research on students revealed their reduced decision-making times in temporal and spatial anticipation tests, with temporal anticipation being more effective.

In sports practice there may be a simultaneous overlap between the two anticipation types and the resulting final benefits. The source of signals of anticipatory reactions in studies on athletes can be movements of individual joints and muscle tension before the performance of a given sports technique. An illustration of this phenomenon can be the behaviour of a tennis player awaiting an opponent's serve, or a fencer's defensive reaction to an opponent's attack based on the observation of activation of the opponent's front and rear leg muscles. As platform posturography and EMG research indicate, an incredibly important component of anticipatory processes is anticipatory postural adjustment (APA). Postural equilibrium mechanisms ensure the stabilization of movement patterns at the very beginning of performing a given technique.

Modern research into degrees of freedom reduction, timing, and anticipation

Following Bernstein the process of motor learning is based on the gradual reduction of degrees of freedom to achieve a state defined as stable. Then the freezing of the entire movement structure occurs. When a given movement is perfected, adjustments are possible, involving simultaneous changes in all involved joints. According to Czyż et al. [16], the lack of interconnections leads to a phase called freeing.

In this context, Piechota et al. [17]carried out an interesting study on sprinters, in which they recorded the EMG signals of selected muscles during the sprint start along with a time interval of about two seconds preceding the take-off, from the command 'Get set'. Comparing the structure of the bioelectric tone of the activated muscles, it turned out that the novice athletes activated significantly more muscles than advanced athletes. A study of the kinematics of various technical actions, including the front kick, e.g. *mae-geri*, on a group of novice and advanced karate practitioners revealed that they the latter were characterized by lower leg joint angles (knee and hip joints during the execution of this technique) [18] than the former. This resulted from simplifying and rationalizing the technique compared with the initial movement models resulting from long years of experience. In addition, a reduced activation time of the involved muscles in response to visual signals of the studied expert karatekas was proven. Both examples confirm unequivocally that the economy and efficiency of expert athletes' sports techniques (movement patterns) is due to the process of overlearning occurring at the higher levels of the central nervous system. In addition, a high level of synergy is noted in terms of speed of execution of actions in conjunction with modified techniques. An important role is played here by the preparatory period, in which the expression of mental factors (focus, concentration, divided attention) contributes to the selection of an appropriate movement program. As the referenced studies show an excellent mastery of movement patterns also resulted in their repeatability in subsequent trials.

In addition to the above-mentioned kinematic and dynamic aspects of reducing degrees of freedom, the new concept of 'perceptual degrees of freedom' [19] displaying analogies to Bernstein's view should also be discussed. It is based on the search for visual information that provides optimal sensorimotor responses, ignoring those visual stimuli that are of little use. For example, in a study of soccer players by Williams & Davids [20] observed that experienced goalkeepers fixated for longer on the opposing player's hip region, the foot supporting the body, and even the head, while novices had more scattered fields of view. In their eye-tracking study of soccer players during their specialist training Zwierko et al. [21] concluded that compared to novices expert players were quicker to locate objects in their field of view. Saccades, i.e. conjugate eye movements, in expert athletes featured higher acceleration, velocity, and post-test duration. An original experiment in this regard was carried out by Witkowski et al. [22], who studied the effectiveness of defensive actions of right-handed fencers in confrontation with left-handed fencers. It turned out that the advantages and superiority of left-handed athletes stemmed from the misperception of their offensive actions by right-handed fencers, who fixated on the position of the opponent's blade, guard, and sword forearm instead of the torso and rear leg muscles, which usually provides effective anticipatory input. Thus perceptual selectiveness – a kind of information reduction – can contribute to the effectiveness of technical actions in various sporting competitions.

When referring to the temporal aspects of movement patterns, timing controlled from the level of the motor cortex of the central nervous system is crucial. In addition to the purposefulness and precision of movements, timing indicators describe the quality of movement patterns. Without the recording of intervals of sensorimotor responses, the concept of movement programs according to Schmidt and Wrisberg [23] would be rendered impossible.

It should be noted that in the world of animals, even in species at higher levels of evolution, the sense of timing is not subject to central control processes. Rather, it can be said that animals sense cycles, such as diurnal cycles, or cycles related to changes in the environment due to specific weather or seasons. The concept of timing is broad and takes into account the latent reaction time and the motor phase (movement time) of sensorimotor responses. From the point of view of control of movements, the timing of activation of muscles involved in motor activities is highly significant. For example, the rhythm and pace of performance of technical actions is also important in sports of artistic expression. In sports based on open movement habits the rhythm of the game is often referred to, while in combat sports it is the choice of pace, i.e. moment to attack the opponent.

Long-term studies using a properly designed EMG system, conducted on martial arts experts and novices (fencing, karate, taekwondo) revealed the following regularities. In simple reactions, expert athletes required 160.83 ms (milliseconds) in the latency phase (RT) and 69.00 ms in the MT phase. The total sensorimotor response was the sum of RT and MT. The RT in novices was 180 ms, while their MT amounted to 68.00 ms. Significant results were achieved by the studied athletes in terms of their choice reactions: experts 238.33ms (RT) and 99.17ms (MT), and novices 299.47 (RT) and 103.07 (MT), respectively. This proves that the increased difficulty scale of the motor task significantly prolonged the RT, and only slightly the MT, with expert athletes processing information for about 60 ms shorter in the RT. These studies demonstrate that RT, also understood as latency or decision-making time, is highly significant. In temporal terms it usually accounts for about 70% of the total sensorimotor response. It should also be noted that an increased RT in both simple and complex reactions always results in increased MT. The above-mentioned system was also used to study timing differences depending on the type of stimulation: visual, auditory and tactile. Observations from the literature that humans respond faster to tactile stimuli, than to auditory stimuli followed by visual stimuli were confirmed.

Closely related to timing in different types of sensorimotor responses is temporal and spatial anticipation. Researchers have proven the greater effectiveness of temporal anticipation over spatial anticipation. These differences occurred in experiments in which participants pressed the buttons and specially integrated pedals of a measuring device [24]. In simple responses the benefit of spatial anticipation, i.e., a reduction in processing time in RT was about 60 ms, while in MT it was about 20 ms. Comparatively, in novice athletes it was 25 ms less in RT, and several ms less in MT than in expert athletes. The hypothesis, consistent with conclusions by Rosenbaum [25], about the essential role of information processes, including the reduction of processing time in choice reactions, is justified here. It is worth adding, however, that the response gains also apply to MT, although to a much lesser extent. What is more, the benefits of reduced processing time affected expert athletes more than novices, demonstrating the importance of long-term motor learning in the formation of desired movement pattern structures. Studies of anticipatory behaviours have been conducted in training conditions during the performance of specific motor activities in fencing [26].

By integrating three research tools: EMG, ground reaction force plates, and the OptiTrack motion capture system, it was possible to obtain time-synchronized indices of muscle activity prior to the movement initiation in sprinters' 100-meter dash start and in fencers performing a forward lunge push on a trainer's signal. It was assumed that the anticipatory phase was the interval between the activation of the stimulus (sound signal in sprinters and movement of the trainer's blade in fencers) and the start of the given movement (MT). Furthermore, the activation of the athletes' muscles in the fore period was recorded. Such an approach made it possible to identify the anticipatory structure of muscle tension, corresponding to previously learned movement programs. Thanks to the use of sEMG and ground reaction force plates, anticipatory postural adjustment (APA) was also evaluated, revealing the anticipatory role of the postural muscles in the studied sports motor activities. It is worth mentioning that the APA phenomenon was also noticed by authors using the same tools in a study of wheelchair fencers, whose postural muscles played a key role during the performance of technical actions. Despite the paresis of the lower limbs, the back and abdominal muscles being the postural muscles of wheelchair fencers were activated first, based on the neurophysiological mechanisms described above [27].

In conclusion, the phenomenon of anticipation is associated with the programming of sensorimotor responses at the central level and in the premotor phase, where the ground force response also plays an important role in synergy with EMG. As proven the shortening of both phases: fore period and reaction time, contributes to the reduction of movement time, thus making the entire motor action more effective.

CONCLUSIONS AND PRACTICAL IMPLICATIONS

There is no doubt that Bernstein's ideas have not lost their relevance in modern times and continue to inspire research ideas and motor learning practice in the area of development of productive and sports motor skills. The focus of the present study is on sports motor skills, following the novice-expert paradigm. This approach provides broader opportunities to interpret motor effects over longer time horizons. The development and acquisition of motor patterns in various sports take years, and their effects appear to be permanent, which does not preclude later modifications. From this perspective the following manifestations of Bernstein's original concept in the application of modern technologies should be mentioned:

Firstly, the so-called contextual interference has become immensely useful in learning motor skills. It involves the use of new activities in learning motor tasks with a similar structure. The point is that tasks similar in their structure are characterized by a high level of interference. This phenomenon is due to a 'peculiar randomization' within the information processes, as opposed to the blocked order methods used so far. The classic transition from one exercise to another after mastering the previous task is inefficient and prolonged in time. Random order methods actively engage students in the learning process owing to constant changes in the stimuli affecting them. They enforce active thinking, permanent control, and comparison with previously acquired skills. Thus new skills are more malleable, reaching a plateau, and do not fluctuate continuously [28].

Secondly, in developing motor skills many habits learned in a long process become highly automatic. For example, an experienced driver after many years of practice concentrates on observing the road without being aware of the movements of their arms and legs. Similarly, a supersonic jet pilot reacts to changing conditions according to automated movement programs in short intervals. In sport, similarities can even be drawn with mid-range basketball players, who subconsciously dribble the ball, while focusing on tactical tasks and game strategy. Similarly, fencers, when performing parries to protect their torso, arm, or head, automatically, as it were, counterattack the opponent, giving primacy to the previously assumed combat tactics. These phenomena were accurately interpreted by Antoinnete Gentile and Zbigniew Czajkowski, who introduced new terms to the area of motor control. Czajkowski [29] used the concept of actions in a state of 'secondary sub consciousness', while Gentile [30, 31], while honouring the concept of implicit learning, used the term 'development of automaticity, without conscious awareness'. This is particularly evident at the championship level in competitive sports. Sport champions often use previously learned movement patterns subconsciously (as some kinds of scripts) to act out different scenarios of events in a certain space and time [32]. The approach presented here is of fundamental importance and allows distinguishing between reflexes that have physiological connotations, and motor habits acquired in a long-term motor learning process involving memory processes and motor imagination.

Thirdly, the results of studies, particularly those concerning the problems of timing and anticipation, prove the objective validity of the significance of RT – the interval from stimulus onset to the first EMG activity – preceding MT. As shown in the referenced experiments, the RT is clearly dominant in a temporal sense. Moreover, when anticipatory factors that occur prior to the sensory-motor response in the fore period are considered, it is justifiable to assert the overwhelming influence of perceptual processes on the quality and speed of execution of motor patterns. Perceptual training is, in addition to physical, technical-tactical and psychological training, the main component of athletes' preparation for high-level sports performance [33]. Perceptual skills allow athletes to respond to the relevant signals in sports competition and disregard disruptive information that reduces the effectiveness of sports combat. It should be emphasized that competition in sports based on open motor habits (team games, racket sports, martial arts) takes place in a time deficit and necessitates maximal reduction of decision-making time and effort expenditure. Numerous studies show that experienced athletes, guided by goal strategy, base their perceptions on long-term memory (LTM) [34]. In addition, thanks to external focus, they control their movement habits better and reduce their muscle tension. This strategy, although prolonging the stimulus detection phase, in effect, comprehensively reduces the entire information processing. The phenomenon of considerable visual fixation and EMG signal reduction in advanced athletes compared to novices has been confirmed by many authors, e.g. Vance et al. [35]. An important factor in further reducing information processing in the response choice phase is perceptual anticipation. Studies of fencers as well as karate and taekwondo practitioners have shown that properly conducted perceptual training affects the sensory system, allowing rapid access to neuronal representations and, through moto neurons, to effectors. Anticipatory information provides a pathway for faster and more accurate choice of sensorimotor responses. This phenomenon clearly occurs in expert athletes and to a lesser extent in novices.

Based on the reviewed research, the main goals to improve skills in the area of perceptual training should be:

- developing the ability to recall and reproduce sport-specific technical-tactical patterns;
- developing the ability to extend visual perception in response to signals related to athletes' postural orientation;
- applying strategies of divided and selective perception (narrow and wide fields of view);
- developing the ability to differentiate stimuli and select among similar information, which is particularly relevant in combat sports;
- consolidating patterns of temporal structure of sensorimotor habits to make their performance independent of the emotional changes that athletes undergo in stressful situations, such as in sports competitions.

These premises gave rise to the proposals of trial-and-error method and overlearning training method inspired by Bernstein's theory and emphasized by Schmidt and Lee [36]. From the perspective of neurophysiology, high mastery of motor skills is conditioned by the cortico-cerebellar-thalamo-cortical loop of the central nervous system. Another observation is that, in essence, the motor learning process is never finished. Depending on environmental requirements it should be constantly corrected and improved.

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