Futurism in Physiology: Nikolai Bernstein, Anticipation, and Kinaesthetic Imagination

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Abstract. The article brings together the history of anticipation with some cutting-edge research on kinaesthetic imagination. It locates N.A. Bernstein's work in the context of both early-twentieth century holism in biology and the wider cultural movement of Futurism. The authors examine Bernstein's attempts to introduce intentionality into physiology and his passionate search for determinants of movements in the future, rather than in the past. These attempts were stimulated by Bernstein's work on specifically human movements, purposeful and wilful, very much unlike the conditional reflexes of Pavlovian dogs. The article also describes the notion of anticipation as conceived by Bernstein as well as later studies of anticipation by contemporary physiologists and phenomenologists. It then introduces the notion of kinaesthetic imagination based on research by scholars of dance and sport. The article concludes with a section on the use of kinaesthetic imagination for rehabilitation of post-stroke patients, quoting from research in progress.

Key words: anticipation, N.A. Bernstein, Futurism, kinaesthetic imagination, intentionality, rehabilitation

"Imagination alone offers me some intimation of what can be".
André Breton, *Manifesto of Surrealism* (1924)

1 Introduction

In the last years of his life Nikolai Aleksandrovich Bernstein published several articles in a journal of wider audience, Science and Life (Nauka i zhizn'). Sometimes these were notes and materials which he had collected for many years. He was a person of the broadest interests: he played piano, drew, assembled radios, constructed models of steam engines and bridges. As one of his later items in Science and Life shows, he was also vividly interested in the issues of imagination, fantasy, anticipation and, as we would now call it, psychosomatic medicine. The article or, rather, a collection of notes, is titled, "Death out of Frightful Expectation of Death". Bernstein retells there two fictional plots: Nikolai Gogol's novella, Viy, and the story by Edgar Poe, The Fall of the House of Usher. What, he believes, these two stories share in common is the influence of anticipation on the person's condition.

Viy is a gothic horror story in which the main character, Khoma, spends three nights in a church by the dead body of a witch. On the third night, the witch comes to life and calls the demons and monsters around her to bring Viy, the chief monster who can see everything, to the church. Khoma sees a horrible, iron face staring at him. Viy points in his direction, and all other monsters leap upon Khoma who then dies from horror. "These are fairy-tales, poetic fantasies", Bernstein comments. "Yet, is anything like this possible in real life? Each of us has, at least once in a lifetime, experienced what a powerful purely physiological impact an anticipation of forthcoming danger can have on us: the face goes pale, the heart beats hurriedly and unevenly, sweat appears on the forehead, etc. All these phenomena are called vegetative reactions, and in such cases they are not responses to a real irritation or impression, but merely to their probabilistic anticipation" [1]. Further the author asks whether a combined vegetative reaction to an anticipated future could reach such a power that it would cause death, and he passes to non-fictional stories. The first one is especially significant. It had been told by Colonel de Rochas who lived in Paris at the turn of the nineteenth and twentieth century and was famous for his interest in hypnosis and suggestion. The story goes that an overseer of a Parisian lycée was so cruel to pupils that they decided to take revenge. Several students locked the tutor in a dark closet and imitated a court trial where they listed all his "crimes". They sentenced him to capital punishment, brought the "guillotine" and announced to him that he had three minutes to prepare for death. They forced him to kneel, exposed his neck, and one of them beat the man on his neck with a wet towel. Then, with laughter, they announced that the joke was over. To their horror, the man was dead [1].

It does not surprise us that Bernstein, who had lived through three wars and through the Red, White and Stalin's terror, reflected on fear and death. Fear of death was an issue on both sides of the Iron Curtain. In 1936, Bernstein's colleague, whose work he knew and appreciated, Adhémar Gelb, died allegedly out of fear for his life [2, 146]. Gelb's co-author and friend, the famous neurologist Kurt Goldstein was arrested by the Gestapo and exiled. While waiting in Amsterdam for an American visa, Goldstein wrote a philosophical treatise, *The Organism* (*Der Aufbau des Organismus*, 1934), where he formulated his "holistic" approach in biology. The chapter on "essential characteristics of the organism in the light of the holistic approach" opens up with the section, *On the Phenomenon of Anxiety.* The author argues that anxiety is one of the main human conditions and courage is the capacity to bear it [3, 229]: "The capacity of bearing anxiety is the manifestation of genuine courage, in which one is ultimately not concerned with things in the world but with threat to existence. Courage, in its final analysis, is nothing but an affirmative answer to the shocks of existence, which must be borne for the actualization of one's own nature. This form of overcoming anxiety requires the ability to view a single experience within a larger context, that is, to assume the 'attitude toward the possible', to have freedom of decision regarding different alternatives" [3, 240]. Thus, Bernstein in the Soviet Union and his colleagues in Nazi Germany were interested in various ways in how the future is represented in the organism: *probabilistic anticipation* and the *attitude toward the possible*.[1]

In this paper, we would like to address the notions of anticipation and kinaesthetic imagination which we understand as ramifications of the category of the future. The category has not always been present in physiology; indeed, throughout the second half of the nineteenth century the physiologists who wanted their discipline to be "objective" and "scientific" tried to purify it from any "vitalism". They firmly grounded their discipline in chemistry and physics and believed that all functions and actions were determined by the organism's structure which could be analysed in chemical and physical terms. But this approach, known as *mechanicism*, became anachronistic by the end of the nineteenth century. At the beginning of the twentieth century a number of biologists, including Jacob von Uexküll, Constantin von Monakow, Kurt Goldstein and Hans Driesh, criticised mechanicism and reductionism and suggested a new, holistic, approach. This approach inspired Bernstein, Luria, Vygotsky and their colleagues across the Soviet border. For many of them an important task became to "rehabilitate" the future as a determinant of human action.

2 The Future as a Determinant of Action

"To Olga, in memory of what will be!" — the poet and Futurist, Igor Terent'ev, signed a copy of his book to a friend[2]. Beginning with F.-T. Marinetti, the Futurists raised the issue of the future in art loudly and even scandalously. They called their main enemy *passeism* — the view that everything is determined by the past. They hoped to replace it by spontaneity, creativity and imagination; they wanted their art and life in general to be determined by the future — a vision of what is not there and what is yet to be created.

Along with the Futurists, physiologists reflected on the fact that human beings could have a "memory of the future". For this, they had to reassess a tradition of conceptualising the organism as a mechanism. The dilemma, teleology versus determinism, provoked long debates. Some biologists sought to reconcile vitalism with mechanicism and to suggest a compromise. Earlier, Karl Ernst von Baer had pointed "to the fact that biological phenomena, particular the phenomena of embryogenesis, required some further set of explanatory principles in addition to the laws of physics and chemistry in order to incorporate the most essential phenomena of life; namely the patently obvious and real existence of auto-regulation and goal-directedness within biological organisms" [5, 274]. It is significant that the very term, *biomechanics*, which Bernstein made heavy use of, had been introduced in the 1880s by German neo-vitalists. Like von Baer earlier, they used embryogenesis as an example of life forces at

[1] We leave out for a general discussion an important question of the distinction between *probability* and *possibility*. I thank Prof. Mihai Nadin for this comment.
[2] Terent'ev's remarkable *Treatis*e *on Total Indecency* was published in Tiflis in 1920 by the Futurist group *41°*; Cf: [4, 202].

work, which could not be entirely explained by the mechanistic approach. They put the stress on the first part of the term, *bio-,* rather than the second, *-mechanics* [6–8].

Later, however, biologists returned to the purely mechanistic view of the organism and paid only lip service to what was "organic" in it. As a result, "biologists have learned to live with a kind of schizophrenic language, employing terms like 'selfish genes' and 'survival machines' to describe the behavior of organisms as if they were somehow purposive yet all the while intending that they are highly complicated mechanisms" [5, ix]. Intentions, drives, purposes were mainly ignored; expectations or anticipation were re-conceptualised as reflexes.

Bernstein stood out as a striking contrast with the latter trend. Early on, he dismissed the interpretation of human learning as the process of acquisition of conditional reflexes. Already in 1924, he gave a talk at the seminar of the Central Institute of Labour where he argued that Pavlov's theory could not explain human skills because it ignored their purposeful character [9]. The Central Institute of Labour became a cradle of Bernstein's biomechanics and his theory of movement. The institute was conceived by a poet, revolutionary and metal worker, Alexei Gastev, in 1920. Gastev was close to the Futurists and he wanted to promote a new culture of work and movement. "The twentieth century", he wrote, "is not just an expression of the machine principle and mass production, it is also a century of industrial and social kinematics <…> The all-increasing hurricane of mechanical kinematics requires a new type, new system, or new culture of conduct" [10, 3–6]. Gastev wanted to "rationalise" work operations and to teach each worker "rationalised" or "normalised" movements. It was important, according to him, for the worker to prepare for the operation by taking the right posture and a general "attitude for work". The term "attitude" obviously relates to intentions more than to causes. No doubt Gastev's ideas influenced Bernstein, who spent the opening and very productive years of his career at the Central Institute of Labour.

The contrast between Pavlov's and Bernstein's theories could be explained by the different phenomena which they respectively studied.[3] Pavlov worked with dogs, immobilised and locked in the "tower of silence", with very limited stimulation. Their reactions were also very limited in range and artificial — they were *conditioned* by the experiment. By contrast, Bernstein studied specifically human movements — work operations. The only time when he compared human and animal movements — in his case, various gaits [11], it was in order to juxtapose humans to animals. "The human being is not a frog, a rabbit or a cat" — he liked to emphasise [12]. Human action is purposeful and meaningful; its initiative does not come from some external stimulus and belongs to the actor who, while performing the movement, is especially active.

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[3] This was suggested to one of us by the late Professor Mikhail Grigorievich Yaroshevsky (1915–2002).

Fig. 1. Nikolai Bernstein in the Central Institute for Physical Culture, Moscow, ca 1947. Courtesy of the Lesgaft National State University of Physical Education, Sport and Health, St.-Petersburg.

We have had already a chance to tell the story of how studying "rationalised" or "normalised" work operations helped Bernstein to advance a new theory of "movement construction" [13; 14]. Later he was called one of the founders of system theory. As early as the mid-1930s, Bernstein wrote: "At every stage of its development, brain is an *organised system*. The qualities and possibilities of the nervous process <…> appear as a necessary result of its organisation and they are in systemic interrelationships determined by the organisation" [15, 325-326; italics in the original]. In his later works Bernstein described how this organisation develops by introducing the notions of essential and non-essential parameters of movement. He called essential parameters, which must be observed, "invariants"; by contrast, non-essential parameters can vary. Which parameters are essential depends on the objective of a particular movement. The objective is formulated both in the language of the neuromuscular apparatus and in the categories of the outer world. The content of the objective determines the construction of the movement. If, Bernstein argued, one trains a speedy movement first in a slow tempo, the construction of the movement will have nothing to do with the objective [16].

By contrast with Pavlov who identified movement with a simple reaction to a stimulus, Bernstein treated it as a process comparable in its complexity with an intellectual act. He introduced new terminology: feedback from the periphery of movement, sensory corrections, the model of the desired future — a model against which to compare the information from the periphery and to correct the actual processes.

For our purposes it is even more important that, speaking of the nervous system correcting the on-going movement, Bernstein introduces the term, *preliminary* corrections. Besides corrections which he calls *secondary* or *post factum*, he suggested a new type of corrections: *preliminary* or *ante factum*.[4] He "discovered" the latter while examining, together with his assistant and sister-in-law, Tatiana Sergeevna Popova, the ontogenesis of walk — the gait of babies and little children:

[4] This work was first published in 1947 under the title "The Coordination of Movements in Ontogenesis" in a collection of works by the Central Institute for Physical Culture, Moscow, and was reprinted in [17].

> At first, in order to maintain the stable length of the step, the child uses to their full extent the mechanisms of proprioception in order to correct the original impulse "epsilon", which has a chance character. Later the secondary (post factum) corrections give place to another, more perfect way of coordination, which provides the nervous system with a pre-emptive (ante factum) account of the impulse intensity depending on the conditions on the periphery. This more precise way of correcting can be called preliminary corrections. It, of course, does not completely cancel secondary corrections; yet the latter now play only a lesser role in correcting and adding to the actual movement [17, 331].

According to Bernstein's former student and an eminent physiologist in his own right, Viktor Semenovich Gurfinkel, Bernstein's logic often dominates the experimental data and compensated for the lack of it [12]. We believe that Bernstein's discovery of preliminary corrections was stimulated by both a special "pike" or "wave" which he had observed in his cyclograms of walking, and the logic of movement in which Bernstein, a Futurist in physiology, included preliminary, ante factum corrections. Later he generalised anticipation — a phenomenon discovered while analysing children's walk — to other kinds of movement, including work operations [17, 332]. The model of the future movement or the model of the desired future was, according to Bernstein, an invariant which defined the organisation of the motor act: "whichever kind of motor activity of higher organisms we analyse, from elementary actions to the chains of work processes, writing, articulation etc., we will not find another leading invariant besides the meaning of the motor objective and the anticipation of the sought for result" [18].

The innovative character of Bernstein's theory and his contribution to the physiology of movement can be hardly overestimated. Yet, because of his criticism of Pavlov, in his own country Bernstein was long out of favour. Even in 1962, at a philosophical symposium, "Consciousness", some speakers still tried to diminish Bernstein's contribution by calling his terminology, including the "model of the desired future", "ultramodern" (E. A. Asratyan, quoted in: [19, 52]. Thus, the critics threw the baby out with the bath water — as it is impossible to explain the role of feedback and sensory corrections without some idea of a model. Only after Bernstein's death and with the coming of cybernetics and system theory to the Soviet Union, was his work duly appreciated. Today the idea that the brain "constantly compares" the actual condition and the desired one is taken for granted, though Bernstein's authorship is rarely remembered.[5]

Between 1957 and 1961 Bernstein took part in the well-known seminar of I. M. Gelfand, M. L. Tsetlin and V. S. Gurfinkel on artificial intelligence [21]. His ideas became known to mathematicians specialising in this area [22]. His hypothesis that the content of the motor objective — the meaning of the movement — is an invariant which determines the organisation of the movement, provided the basis for the theory of *non-individualised control* of complex systems and for the principle of minimal interaction in the process of such control [23; 24]. Some of his concepts found experimental proofs: thus, M. L. Shik with co-authors discovered the central generator of walking [25]. They stimulated studies of *motor synergies* as flexible adaptive structures which take shape in the course of complex multi-joint movements [26–29]. When some of Bernstein's works were translated and published in the West [30],[6] they were well received in the nascent cognitive sciences. The American psychologist, Howard Gardner, introduced the notion of bodily-kinaesthetic intelligence in the framework of his theory of multiple intelligence. Gardner referred to Bernstein as to one of the first to have brought together the use of the body and cognition [32, 208 ref.]. To illustrate the point that movement is cognitive and intellectual, we would like to mention the story which Gurfinkel told to one of us. In the time just after World War Two, Bernstein taught at the Institute of Physical Culture in Moscow, and Gurfinkel was his PhD student. Once Bernstein examined a female student, a high diver. Undecided about which mark to give to her, he asked an extra question: to give an example of a cyclic movement. Her answer — "high diving" — was clearly wrong. And yet, Bernstein gave her the highest mark. "She knows how to dive", he explained his decision [12; 33].

3 Anticipation and Kinaesthetic Imagination

[5] Alain Berthoz and Jean-Luc Petit remind us that the idea that the "brain makes predictions and anticipations" has its origins in Bernstein's work [20, 88].

[6] Unfortunately, Bernstein's fundamental work *On the Construction of Movements* (1947) [31] has never been translated into European languages.

The concept of anticipation is not new; medical and other researchers wrote about anticipation in the course of the nineteenth century. The mental physiologist W. B. Carpenter introduced the concept *ideo-motor action* to describe the way self-willed or automatic thoughts took control over the bodily organs; the concept provided a basic framework for understanding the course and generation of illness [34, 13]. The term, the *anticipating* (sic!) *imagination*, was not uncommon in popular literature on science, and even in Christian theology. It was used, for instance, to explain psychic phenomena which could be observed at seances of table-turning. The unconscious was widely understood in terms of expectations and sub-conscious anticipation. Later, however, Hayward argues [34, 12], the interpretation of the unconscious processes changed: thus, Freud linked them to past events, especially to childhood memories, rather than to the anticipated future. The unconscious psyche was now understood as a collection of traumatic memories and frustrated desires rather than as a capacity for anticipating events. This interpretation Pavlov shared with Freud, in spite of all their disagreement. By contrast with Pavlov and many others, Bernstein was interested in the determination of the action by the future. His brief article in *Science and Life*, with which we opened this paper, confirmed this once again.

By quoting Bernstein's productive formula "Posture is a preparation for action" [20, 88], the physiologist Alain Berthoz reminded us that Bernstein was one of the first to conceive anticipation as a constructive element of movement. In the early 2000s, Berthoz, who considers himself Bernstein's student, and the philosopher Jean-Luc Petit wrote a book-length study *The Physiology and Phenomenology of Action*, quoted above. Amongst other questions, they touch on two linked concepts: *anticipation* and *kinaesthetic imagination*. They saw the roots of the concepts in Kant's philosophy. Kant wrote that "motion <…> considered as the describing of a space, is a pure act of the successive synthesis of the manifold in outer intuition in general by means of the productive imagination and belongs not only to geometry, but even to transcendental philosophy" [20, 92–93]. Following Kant, the authors distinguished between *schema* — an image which implies vision, and *schemata* (*scheme*) — a powerful concept in psychology which implies action, movement and the body. Imagination is a faculty of schemata. The key idea underlying Kant's *schematism*, as Berthoz and Petit understood it, is our constant schematisation of experience. Kant attributed this structure either to the faculty of imagination or to the faculty of understanding claiming that, to the extent that it proceeds from our spontaneity, it consists of a natural poetics [20, 117–119]. How, Berthoz and Petit asked, can these formal aspects be manifest in something, namely the subject, who is essentially temporal? They answered: the formal aspects are manifest through the *actions of anticipation* accomplished by the perceiving subject. In relation to this, Berthoz referred to his memories from 1970 when he was a guest of the Russian physiologist A.S. Batuev at the Pavlov Institute in Leningrad. He remembered his joy on seeing the neuronal activity of the auditory system of an animal in Batuev's laboratory. These neurones responded vigorously to the natural meowing of a cat but were completely indifferent to any pure sound in the same wave frequency. The brain, Berthoz commented, is definitely interested in meaningful events in the physical world belonging to its *Umwelt*. "The decisive step in neurophysiology", he claims, "is therefore a transition from a bottom-up neurophysiology to a top-down neurophysiology, a physiology of anticipation" [20, 129–130].

It might be suggested that Berthoz and Petit inherited this stand from the phenomenologist, Maurice Merleau-Ponty. The latter argued that, in order for spectators to activate their kinaesthetic imagination, they need to experience participation in the performer's movement rhythms. Merleau-Ponty discussed kinaesthesia in terms of "intentionality" or "goal-directedness". He argued that an attitude of openness towards a future movement was inseparable from a corporeal experience in the present, which he described as being neither a movement nor a mental representation of a movement, but rather "an anticipation of, or arrival at, the objective <…> ensured by the body itself as a motor power, a 'motor project' <…> a 'motor intentionality'" [35, 187]. The French kinaesiologist and dance scholar, Hubert Godard, continues the tradition. He argues that "virtual" (anticipated or imagined) movement is itself a physical event. Godard describes as "pre-movement" the process whereby a set of muscles contracts in anticipation of a movement to be performed by a different part of the body. For instance, if we ask a person in the upright position to raise her arm, the first muscles to contract will be those of the ankle and leg: thus the body anticipates the need for balancing the changed center of gravity that will result from lifting the arm. Modern neuroscience contends that such a pre-movement starts about a quarter of a second before the main action (here, the raising of the arm) begins, indicating that pre-movement is not a localised reflex action but rather, originates in the brain triggered by the formation of the intention to move [35, 13].

The philosopher Susan A. J. Stuart writes on the role of anticipation and connected notions of *apperception* and kinaesthetic imagination [36; 37]. She and others use the wonderful word *plenisentient* to describe the way the body is switched on to the world, perceiving, receiving, imagining, anticipating, and actuating. The *plenisentient* experience of movement assures the deep pre-cognitive kinaesthetic relationships with the world which makes its conceptualisation possible.

The term *kinaesthetic imagination* was perhaps introduced in the first decades of the twentieth century. The American dance scholar John Martin argued that we all are equipped with a sixth sense of kinaesthesis – the capacity to act gracefully and to apprehend directly the actions or the dynamic abilities of other people or objects [32, 228]. Even earlier, William James in his famous *Principles of Psychology* (in the chapter on imagination) discussed the issue of motor imagery: whether it was a "resuscitated feeling" arising in the body parts that had been influenced by prior movements. It was not until the 1980s that the true motor nature of motor imagery was fully recognised. This move was a noted contribution of sport psychologists [38, v].

As the phenomenologist Maxine Sheets-Johnstone shows, we need kinaesthetic imagination both for performing our own movements and *perceiving* the motion of other persons and objects. For instance, in the case of a dancer moving along a circular line, "we form an imaginative Gestalt of the movement by apprehending each moment of the circle as a spatial-temporal present in relation to a spatial-temporal past and future: the present is a flight out of the past towards a future. It is a transitory moment of an imaginative spatial-temporal whole and not an isolated present. Consequently, there is not a succession of images but a single and unbroken circular line" [39, 116]. This is undoubtedly a product of kinaesthetic imagination.

For a number of years, Dee Reynolds, with collaborators, has been working on a project "Watching Dance", to investigate *kinaesthetic empathy* — an ability to perceive and understand movements (including dance) of other people. She also uses the term *kinesthetic imagination* for the bringing about of "movement events that disrupt normative, habitual ways of using energy in movement and produce innovations in production, distribution, expenditure and retention of energy in the body". These acts, she claims, involve a delicate balance between determinism and agency. The function of kinaesthetic imagination can be viewed as an activity that works with sign systems to destabilize fixed meaning and representations [35, 4].

Kinaesthetic imagination can have multiple practical outcomes. Virtual or imagined movement can be used to learn new skills, as happens when athletes repeatedly visualise correctly executed movements when learning to perform difficult manoeuvres. Mental rehearsal is now included in rehabilitation procedures for patients suffering from pathological motor impairments and associated troubles, like phantom pain and post-stroke and post-traumatic movement disorders. Some recent studies suggest that activation of the motor system during motor imagery is not identical to that during motor execution (the distribution of activity in the two modalities only partially overlaps, and the activity within the motor cortex is weaker during imagery than during execution) [38, vi]. Yet, kinaesthetic imagination has found its way into clinical practice and research.

4 Kinaesthetic Imagining of Movements: Clinical Application

The functional topography of the primary motor cortex has demonstrated the cortex's plasticity, as, for instance, a result of training. This research has recently stimulated works on the brain-computer interface (BCI) based on kinaesthetic imagination of movement [40]. It has been shown that the intact areas of the brain can take up the functions of the damaged areas, so that movements can be restored even several years after a stroke or trauma has damaged the brain structure [41; 42]. This has opened new possibilities for neuro-rehabilitation, and researchers have formulated some important principles of intensive, regular, and motivated movements training [43].

In the process of restoring movements with the help of the BCI, the patient is asked to reproduce the state associated with kinaesthetic imagination of a particular movement. If the patient can securely reproduce this state, he receives visual feedback. During training sessions the electroencephalogram (EEG) is recorded, and the BCI classifier recognises patterns of electric activity of the brain which correspond to imagining the movement. Multiple repetition of the state can assure the connection between intention and the corresponding activity of the brain, thus improving the quality of motor control. Rehabilitation is especially efficient in conditions when the BCI classifier has recognised the state and, at the same time, the movement is performed (for example with the help of an exoskeleton). Realised by the exoskeleton, the desired movement provides, by means of proprioceptive feedback, stimulation of sensorimotor areas of the brain. The stimulation, in its turn, contributes to brain's plasticity.

The neurophysiological foundation of BCI based on imagining movements lies in the alterations of μ- and β-rhythms. Both movement and the preparation for movement in a particular executive organ are usually accompanied by a decrease of μ- and β- rhythms in the cortical representation of the organ. This decrease is known as *event-related desynchronization — ERD* [44; 45]. By contrast, the increase of μ-rhythms, *event-related synchronization — ERS*, takes place in the brain areas of organs not involved in the performance of the movement [44].

The high efficiency of the BCI based on imagining movement can be accounted for by the fact that the *ERD* and *ERS* reactions take place both in the case of an actual performance of the movement and in the case of imagining the movement. There is an important difference, however, between visual and kinaesthetic imagination of movement: the latter activates, at least partially, the same brain areas as the real movement, while the former activates mainly the visual areas of the cortex [46–48]. As a result, *ERD* and *ERS* reactions arise when one imagines movements *kinaesthetically*, rather than visually. Representations of executive organs are widely spread on the surface of the cortex [49]. Imagining movements of various organs therefore creates a different distribution of activity at the cortical surface and, respectively, different spatial patterns of electric activity in the brain. This facilitates the task of the BCI classifier.

During Bernstein's time, the task of decoding the person's thoughts and intentions by signals from the brain was not possible because of the high variability and small resolution of these signals. Besides, the BCI requires analysing brain signals in real time, and until recently technology for this was either absent or too expensive. Yet, in the last twenty years, the situation has radically changed. The number of research teams and of publications on the topic has grown quickly [50; 51]. Researchers have discerned patterns of brain electric activity characteristic for both performing and imagining movement that could be potentially used for the BCI.

BCI applications for neurorehabilitation have not yet stepped out beyond the laboratory walls. Yet, first clinical results are promising [52–54]. Below we give an example of restoring the motor function of the hand in an after stroke female patient who underwent a rehabilitation course with the help of the BCI with the exoskeleton of the hand.[7]

Fig. 2. Rehabilitation procedure with the BCI + exoskeleton.

The general research scheme is shown on Fig. 2. The patient sat in a special comfortable armchair in front of the monitor reading visual instructions and receiving visual feedback. The exoskeleton was put around the patient's

[7] Data collected in the framework of the project, "Developing the method of rehabilitation for post-stroke and post-traumatic patients with the help of the exoskeleton of the hand connected to the brain-computer interface based on classification of EEG patterns corresponding to the imagination of movements", at the N.I. Pirogov Russian National Medical Research University, Contract no. 0373100108213000320–45551.

paretic hand. On the head, the patient wore an EEG-hat with 32 electrodes filled with conductive gel. During the experiment, the surface EEG was registered. The BCI classifier recognised EEG patterns corresponding to three states: kinaesthetic imagination of opening the right hand, kinaesthetic imagination of opening the left hand, and the relaxed state. The instructions to reproduce these states were given in a random order. In the case of successful recognition, the exoskeleton opened the patient's paretic hand. The basic version of the experimental protocol included three sessions of training to control the exoskeleton action by imagination with the help of the BCI. The length of each session was ten minutes. The procedure was repeated daily, for ten days.

For the evaluation of the success in restoring hand mobility, the so-called kinematic portrait of the patient was recorded: movements with the maximum possible amplitude and at a comfortable velocity in all degrees of freedom by the paretic arm and symmetrical movements by the healthy arm. The movements of the healthy arm were taken for the individual norm. The movements were recorded with the help of four sensors of the electromagnetic system trakStar (Ascension Technology Corp.) fixed on the hand, the forearm, the upper arm, and the scapula. The recorded data was used to calculate rotation angles corresponding to flexion-extension and abduction-adduction in the wrist joint; to flexion-extension and pronation-supination in the elbow joint; to flexion-extension, abduction-adduction, and rotation around the vertical axe of the upper arm in the shoulder joint [55].

Fig. 3 and 4 show the dynamics of movement restoration, illustrated by two movements: flexion-extension in the wrist joint (Fig. 3) and flexion-extension in the elbow joint (Fig. 4).

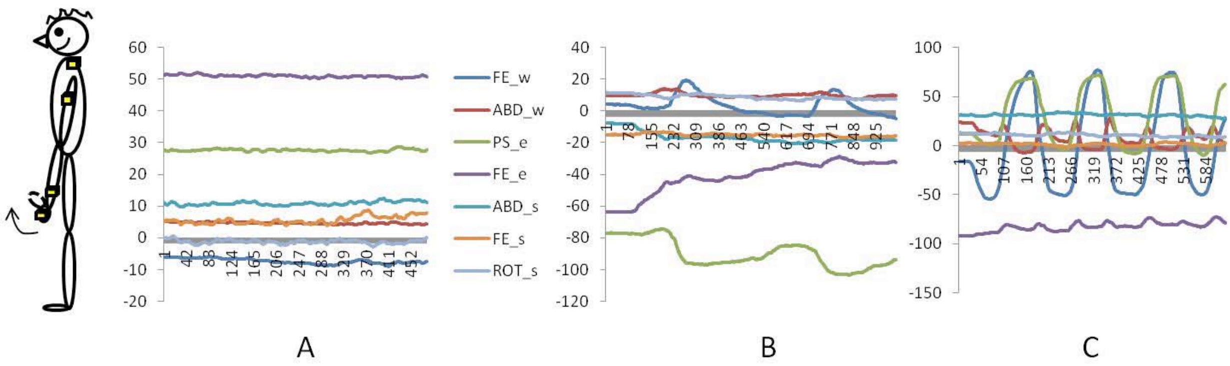

Fig. 3. Time courses of joint angles during flexion-extension in the wrist joint.
The angles are in degrees, each time-point of the abscissa axis corresponds to 10 ms. FE_w – flexion-extension, ABD_w – abduction-adduction in the wrist joint, PS_e – pronation-supination, FE_e – flexion-extension in the elbow joint, ABD_s – abduction-adduction, FE_s – flexion-extension, ROT_s – rotation around the vertical axe of the upper arm in the shoulder joint. A – before rehabilitation procedures, B – after ten sessions, C – movement of the healthy arm (individual norm)

Before the beginning of rehabilitation procedures, the patient was unable to perform flexion-extension in the wrist joint (Fig. 3A). After ten procedures, the patient could already perform the movements, although with a very small amplitude of 20° (Fig. 3B), compared with 120° in the norm (Fig. 3C). Though the patient was instructed to "perform only one given movement", this movement was accompanied by movements in other joints even in the healthy arm. Thus, the instruction "to perform flexion-extension in the wrist joint" in the healthy also involved pronation-supination in the elbow joint (Fig. 3C). After ten procedures, pronation-supination appeared in the paretic arm, too (Fig. 3B), so that the movement under restoration was reaching the norm. Flexion-extension in the elbow joint of the paretic arm was also closer to the norm, both from the point of view of the amplitude of joint angles and in relation to their contribution to the movement (Fig. 4).

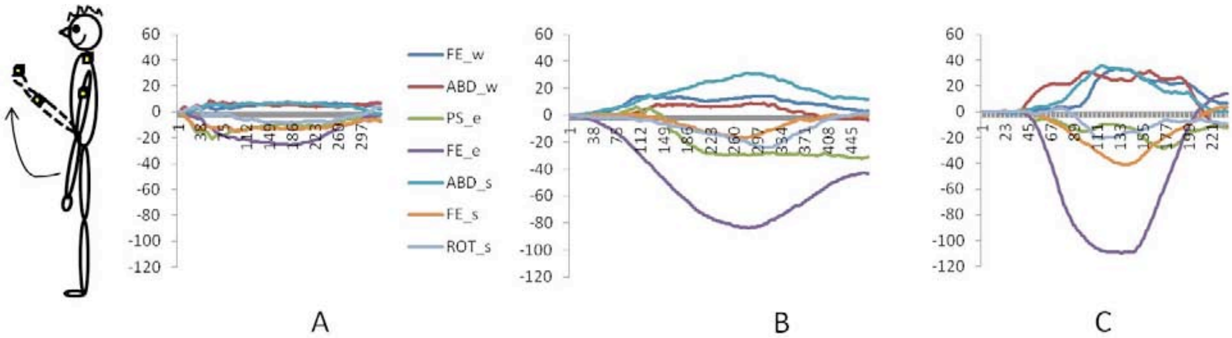

Fig. 4. Time courses of joint angles during flexion-extension in the elbow joint. The angles are in degrees, each time-point of the abscissa axis corresponds to 10 ms. FE_w – flexion-extension, ABD_w – abduction-adduction in the wrist joint, PS_e – pronation-supination, FE_e - flexion-extension in the elbow joint, ABD_s - abduction-adduction, FE_s – flexion-extension, ROT_s – rotation around the vertical axe of the upper arm in the shoulder joint. A – before rehabilitation procedures, B – after ten sessions, C – movement of the healthy arm (individual norm).

The results of biomechanical analysis presented in Fig. 3 and Fig. 4 demonstrate positive dynamics in the restoration of motor function in the course of rehabilitation following the BCI + exoskeleton technology. Although the exoskeleton opened only the wrist joint, there was an improvement in mobility in all degrees of freedom of the arm, which can be observed in the lager amplitude movements in the elbow joint (Fig. 4). We ascribe this result to the beneficial influence of kinaesthetic imagination on motor function.

Biomechanical analysis of the multiple-joint movement of arms and legs as a method of objective evaluation of motor function continues Bernstein's tradition of analysing work movements [56]. Started in the 1920s in the Central Institute of Labour, Bernstein's experiments developed into a new theory of movement and a new approach, physiology of activity, in which the concepts of anticipation and kinaesthetic imagination assumed a firm position.

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