New Pages in the Biography of Nikolai Alexandrovich Bernstein

Vera L. Talis

> *It seems... that the fundamental questions raised by Bernstein in 1962 remain equally fundamental and equally unanswered 20 years later. We may optimistically suggest that they will provide many individuals with a way to pass the time for the next 20 years* (Agarwail and Gottlieb [1])

> *At present, theoretical neuroscience may be considered an independent branch of brain science. The importance of the studies by N.A. Bernstein in this respect may be compared to the importance of Maimonides' reform of Judaism, Luther's reform of Christianity, or Maxwell's revolution in physics* (Latash [2])

Abstract Nikolai Alexandrovich Bernstein (1896–1966) is well known today primarily for formulating the problem of redundant degrees of freedom and their elimination in motor control, as well as his hierarchical theory of movement coordination. This paper aims to uncover new pages in the biography of N.A. Bernstein, based on materials from the archive of his nephew Alexander Sergeevich Bernstein, as well as recent interviews with the former pupils of N.A. Bernstein. Concentrated around several interdisciplinary seminars, they grew into a young generation of physiologists in the late sixties and made remarkable contributions inspired by Bernstein's new principles of neuroscience. These include the discovery of the spinal automatism of stepping in the cat, the "equilibrium point" hypothesis, the hindlimb wiping reflex of the frog as an example of a targeted trajectory organized at the spinal level, and the probabilistic prognosis in human activity.

Keywords Motion · Neuroscience · Motor control · Physiology

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1 Introduction

Only a great optimist might think that science benefited from the fact that Nikolai Alexandrovich Bernstein (1896–1966) was fired from all his positions at the end of the 1940s. It was after this that he started working on his final articles and books, and summarizing experimental material that he had gathered before, as well as the data of young researchers who visited him at home. It is possible, however, that if it were not for this fact, Bernstein would have not become an icon at the beginning of the 1960s, when the worldwide interest in cybernetics reached Russia [3]. In this paper, we intend to reveal new pages of Bernstein's biography, reflected in his letters and interviews with his pupils and relatives. After half a century from his death, they considered themselves lucky to have known a man of genius.

2 Childhood and Youth

Bernstein descended from a family of doctors. His father Alexander Nikolaevich Bernstein (1870–1922) was not only a well-known Moscow physician, but also a broadly educated scholar who laid foundations for the specialization and progress of Russian psychiatry. Nikolai's grandfather Nathan Osipovich Bernstein was the chairman of the Odessa Society of Physicians.

In 1913, Nikolai graduated from high school with a silver medal and was accepted at the Department of History and Philology of Moscow University. He was interested in languages and philosophy. But in August 1914 the war broke out. Like the rest of the country, the young generation of the Bernstein family was swept by a wave of patriotism. Nikolai transferred to the Medical Department of the University. In the fall of 1914, he began the new school year as a medical student (Fig. 1). In the spring of 1919, he graduated from the First Moscow University, obtained his medical degree, and was drafted into the Red Army as a doctor [4, 5]. In spring 1921, Bernstein came back from the front. His father helped him to get a job in the field, and he became a physician at the Gilyarovsky Psychiatric Clinic. After his father's death in 1922, he took over his practice. However, in August 1922, he met Alexey Kapitonovich Gastev—and so began Bernstein's famous period of work at the Central Institute of Labor.

As for Nikolai's younger brother, Sergei Alexandrovich Bernstein, he kept the railroad passion inherited from his mother Aleksandra Karlovna Bernstein (nee Ioganson, 1867–1941) and her father, a lineman on the railway. By 1921, Sergei graduated from the Department of Physics and Mathematics of Moscow University, and in 1926 from the Moscow Railroad Institute. During his studies at Moscow University he met Tatyana Popova (see the history of her family in [6]) and married her in 1922. Later on, she would join Bernstein's lab at the Central Institute of Labor.

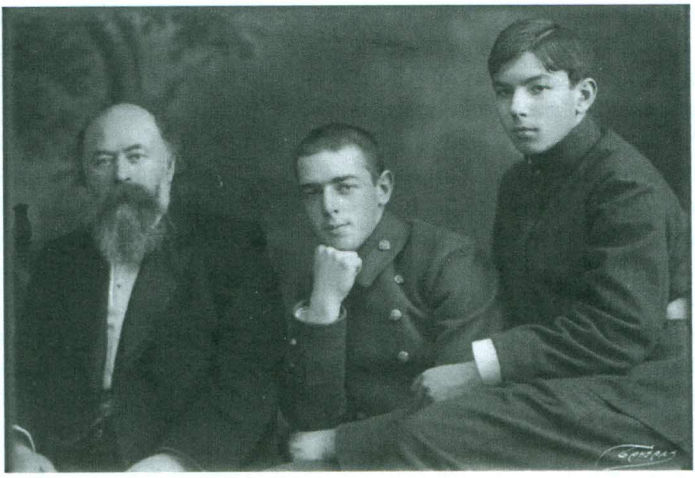

Fig. 1 Alexander Nikolaevich Bernstein with his sons Nikolai and Sergei, 1916 (courtesy of A.S. Bernstein)

3 After 1922

Tatyana Popova wrote the following to her husband Sergei Bernstein in 1924:

> The Central Institute of Labor is a new Institute... Everything is done in a new manner, not in the way it was done by the bourgeoisie. The Institute is striving to introduce science into production. The interests of the director are those of a metalworker, therefore the Institute studies mostly the work of a metalworker and his two main procedures: chiseling and filing [4].

In 1925, Bernstein left the Central Institute of Labor, and over the next decade or so assumed multiple positions at various institutions, including the Institute of Psychology (1925–1927), State Institute of Labor Preservation (1927–1933), State Institute of Musical Sciences ("Gosudarstvennyi Institut Musikalnikh Nauk"—GIMN) (1928–1940), Scientific Research Bureau Of Prosthetic Appliances (1932–1940), the All-Union Institute of Experimental Medicine (1933–1937), Central Institute of Physical Culture (Centralinyi Nauchno-Issledovatel'skyi Institut Fizkul'turi"—CNIIFK) (1936–1941).

All this time Tatyana Bernstein, née Popova (1902–1992), worked with Nikolai Bernstein and was one of his main assistants. They left the Central Institute of Labor together to continue their joint work on finger and hand movements of piano players, hand stamp (1927–1929), and the locomotion of children (up until 1940). With N.A. Bernstein and Z.V. Mogil'anskaya, Popova developed a methodology for analyzing biomechanical measurements [7, 8]. She continued her work on child locomotion after 1943, but stopped working and devoted herself fully to the family at the end of 1947 (from the interview with A.S. Bernstein, 2010). Her husband Sergei Alexandrovich Bernstein was already ill in 1947 and died in 1958, at the age of 56. His collected works were published after his death [9].

The broad scope of Nikolai Bernstein's and Popova's research required participants to be well acquainted with the works of the best physiology laboratories worldwide. In 1929, Bernstein traveled abroad for three months. He visited Institut Pasteur, Institut de Marey, Laboratoire de psychotechnique (of J.-M. Lahy[1]) at the Hospital St.Anne in Paris. For most of his time in Europe in 1929, he worked at the Kaiser-Wilhelm-Institut für Arbeitpsychologie in Dortmund due to long-term contact with Edgar Atzler (editor of the journal "Arbeitsphysiologie"). Bernstein also visited Albrecht Bethe and Ernst Simonsons's lab in Frankfurt. In Paris and Dortmund, Bernstein delivered lectures and demonstrated the use of cyclogrammetry methods and devices [5].

During this trip, Nikolai wrote personal letters daily to his wife and colleague Anna Isaakovna Rudnik, brother Sergei, sister-in-law Tatyana Popova, and mother Alexandra Karlovna. In one of his letters he wrote:

> They keep saying at Laugier's[2] that a biomechanics branch [of the Moscow Institute, VT] will be formed here. They may even send some people to study in Moscow. In any case, we are working on this! .... On Monday I'll see Langevin,[3] and I've started packing my Parisian possessions. It's time to move on! Dear Nyuta, please, go through the drawers 1 or 2 of my desk and try to find the drafts of the captions to the figures of the French article... Dig thoroughly and send them to me in Dortmund. Further, in drawer 4 there must be a thick envelope that has the copies of the GIMN curves. Please send me Igumnov's[4] accelerando, or if its reprint is missing, the German copy of the GIMN article. Further, ask Tatyana to get from drawer 6 the analysis of the pathological image negative that she made. Then have her draw it again in detail for copying, indicating the period of the double step, the f_{yH} curve, and send it to me (26/X,1929, to A. I. Rudnik).

The picture of the table with the numbering of the drawers was enclosed with the letter. About the meeting with Langevin Bernstein wrote:

> ...This morning I went to see old Langevin... He was very nice and attentive. I didn't feel shy while speaking with him and told him in French freely everything I needed. I showed him the atlas[5] which he, being a physicist, quickly understood and then told him about the difficulties (fundamental ones) that we face in mathematical analysis and integration. He grasps quickly and accurately everything you tell him (much quicker and more subtly than uncle Seryozha, entre nous) (28/X, 1929).

Sergei Nathanovich Bernstein (1880–1968), mentioned as uncle Seryozha in this letter (partly published in [10]), was the uncle of Nikolai and Sergei, the younger brother of his father. He was a great mathematician who in his youth presented a solution to Hilbert's 19th problem, only four years after David Hilbert's presentation of his famous paper on 23 unsolved mathematical problems!

The method of cyclogrammetry elaborated by Bernstein at the Central Institute of Labor (1921–1925) allowed him to register movement kinematics with

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[1]Lahy, Jean-Maurice (1872–1943)—French psychologist and sociologist.

[2]Laugier, Henri (1888–1973)—French physiologist, the first director of CNRS (1939–1942).

[3]Langevin, Paul (1872–1946)—prominent French physicist.

[4]Igumnov, Konstantin Nikolaevich (1873–1948)—famous Russian pianist.

[5]"Atlas des Ganges und Laufes des Menschen"—unpublished, now in Dortmund.

150–200 frames/s. In 1928 Bernstein wrote [11], "While studying the movement biodynamics involved in cutting with a chisel, I was able to show that it is impossible to alter selectively any one given detail in this movement without affecting others." Bernstein concluded that the joints were not acting independently but correcting each other's errors. This observation suggested that the central nervous system (CNS) does not follow a unique solution to the problem over repetitive strikes, but rather uses a whole variety of joint trajectories to assure more accurate (less variable) performance of the task [12]. The analysis of labor movements' dynamics showed that inertial forces are the dominant factors the CNS must control to produce accurate movement [13]. In the mid-1930s, Bernstein stated that "the reflex is not an element of an action, but an elementary action" [14], thus showing his critical attitude to generalizing the reflex theory of Ivan Petrovich Pavlov (1849–1936) (Figs. 2 and 3).

In 1935 Bernstein summarized the "principle of equal simplicity" in his paper [15]. Bernstein presented this paper to Norbert Wiener in 1960 [10], which proves how important it was for him. "The principle of equal simplicity" states that a given objective, for example making circular movements with an outstretched arm, can be performed with equal ease (or simplicity) in front of or sideward of the body. This is not a trivial observation considering that the execution of circular movements in different work spaces requires different sets of muscles. Bernstein reasoned that a stored movement engram used to launch an intentional motor act does not include the metric definition of the muscle actions required for goal achievement. According to Bernstein, motor control is thus organized in at least two different hierarchical levels: upper, goal-related level(s) and lower level(s) responsible for metric execution. Nowadays this principle has been confirmed by studies in monkeys performing a bimanual task, where metric changes in action execution were induced by constraints or lesions of the supplementary motor area. In both situations, however, bimanual coordination remained uncompromised [16].

Analyzing skilled, "least automatic" performance, Bernstein formulated the essential problem of motor control as that of "overcoming the redundant degrees of freedom of our movement organs, i.e. turning the movement organs into controllable systems". Later on in the 1960s, when Bernstein died, his pupils used to call the problem of control in a system with many degrees of freedom the "Bernstein problem" (from the interview with Berkinblit, 2010)—a term now widely employed in the literature [17–19]. In 1939, Bernstein started to write his main book "On the Construction of Movements", where he formulated the hierarchical theory of motor coordination.[6] A detailed thesis of the first chapters of the book was published in the journal "Theory and Practice of Physical Culture" in 1940, but the work was interrupted by the Second World War.[7] In 1945, the book was already in press, but

[6]Let us note here that Bernstein himself named this book in English "On the Structure of Movements" (List of publications of N.A. Bernstein, Archives of Russian Academy of Medicine).

[7]In September 1941, Bernstein's family was evacuated to the city of Ulan Ude in Siberia, the capital of Buryat Mongolian Autonomous Republic of USSR. It was impossible to continue research there. Bernstein became the head of the Department of Biology at the Pedagogical

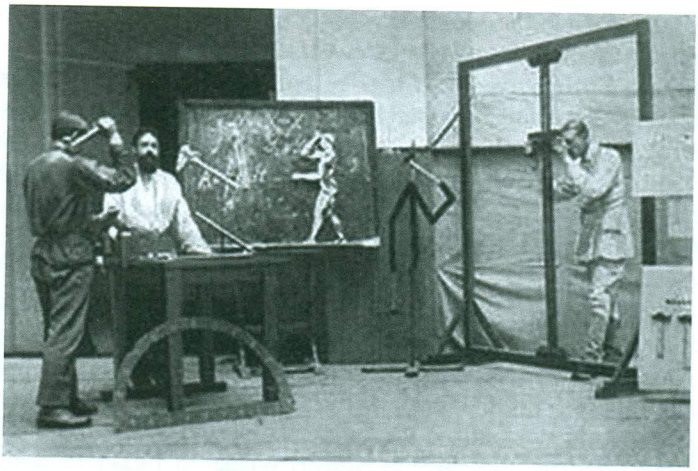


Fig. 2 The Central Institute of Labor (N.A. Bernstein in the *center*), 1923 (courtesy of A.I. Smirnov)

Fig. 3 The registration of striking piano keys. The transfer of the middle finger of right hand for the octave (C2—C3 and back) by the motion of the forearm and hand, 1925 (courtesy of A.I. Smirnov)

(Footnote 7 continued)

Institute, and gave lectures on human anatomy, histology, and general physiology. In his free time, he put together the "Five-place decimal logarithm tables for numbers from 1 up to 10^{10}" based on his own calculations, which was the sole work indexed in his bibliography of 1942. At the same time, his brother Sergei moved to Tashkent where his Academy of Armed Forces was housed at the time. The living conditions were better there, and he arranged for Nikolai's family to move to Tashkent in September 1942. While there, Bernstein worked at the Republican Sanitary Institute of the Ministry of Health of the Uzbek Republic. In June 1943, after the course of the war had shifted, Bernstein was able to return to Moscow.

it was published only in 1947, bearing a dedication to the "blessed, everlasting memory of comrades who perished for the Soviet Motherland." Bernstein was awarded the highest scientific prize of the USSR, the Stalin Prize for this work in the following year. At that time Bernstein was married to his second wife and colleague Natalya Alexandrovna Gurvich (1912–1968) and had a son Alexander (1938–1993).

4 After 1948

The end of 1948 and the beginning of 1949 was a crucial time in the life of Bernstein. In March 1949 he was forced to leave the Moscow Institute of Prosthetic Appliances, in April 1949—the CNIIFK. He was dismissed from all the laboratories that he had created, and his experiments were stopped. Daniella Ginzburg, Bernstein's post-graduate student at that time recalled: "The "witch-hunt" grew worse, involving more and more people, and ruining their reputations. People were divided into two camps—decent and indecent. At the beginning of 1949, the infamous anti-Semitic campaign "against cosmopolitism" broke out. At the Institute of Physical Culture the atmosphere was much worse than in Moscow University, where I had studied before, given the intellectual and cultural level of its staff. At the all-Institute meeting, the faculty-athletes called Nikolai Alexandrovich an "uprooted cosmopolite." When Bernstein was allowed to speak, he said: "Why do you call me an uprooted cosmopolite? I know my father and even my grandfather very well. My father was a famous Moscow physician. Therefore I cannot be an uprooted cosmopolite." I recall another absurd criticism: he was accused of being that very Bernstein who had revised the teaching of Marx. The confusion happened because the name of the German social democrat was familiar from the class of "Marxism-Leninism" that everybody had taken, whereas in fact, he was just a namesake of Nikolai Alexandrovich. When his laboratory members were asked to speak at the meeting, everybody was expected "to throw a stone" at Nikolai Alexandrovich. I was very young, and a recent student. Marxism was fresh in my memory. I just named the dates of life of the Bernstein who had revised Marx, so that they "could compare those dates if they hadn't forgotten simple arithmetic that was taught in secondary school." I put it exactly this way. As a result, I was expelled from Komsomol and also from post-graduate course.... It was not a purely anti-Semitic action; it was rather a persecution of an outstanding scientist mixed with envy and complete lack of understanding. It was as if a doctor who was treating people with cholera during an epidemic was accused by ignorant peasants of infecting them" (from the interview with D.A. Ginzburg, 2009) (Figs. 4 and 5).

Iosif Feigenberg—the first biographer of Bernstein, wrote in his book [5]: "Until 1948 at least several significant publications by Bernstein would appear in scientific journals every year. But now his articles are being rejected. In 1949 only a 2-page

Fig. 4 *Left* N.A. Bernstein and his son Alexander on the boat. Moscow, Ostankino, 1948 (courtesy of D.A. Ginzburg). *Right* Bernstein's passport photo (around 1950) (courtesy of T.I. Pavlova)

КРИТИКА И БИБЛИОГРАФИЯ

ПРОТИВ ВУЛЬГАРИЗАЦИИ ТЕОРИИ ФИЗИЧЕСКОГО ВОСПИТАНИЯ

Fig. 5 "Pravda"—the main official newspaper of the Communist Party in Soviet times. The article "Against the vulgarization of physical education theory" (August 21, 1950) condemns the anti-Pavlovian position of Bernstein. It was published right after the notorious "Pavlovian" Joint session of the Academy of Science of the USSR and the Academy of Medical Science (28 June–4 July 1950)

thesis of his presentation is published by the Institute of Physical Culture. After that—complete silence for 4 years (1950–1953). However, even after Stalin's death and a period of "thaw" that came with it, the publication of Bernstein's essential works remains impossible….Only in 1961 the "conspiracy of silence" that lasted twelve years (1949–1960) comes to an end!"

5 Moscow Motor Control School in the Late Sixties

Young scientists unsatisfied with the official pseudo-Pavlovian physiology in Soviet Russia visited Bernstein at home and incorporated his ideas into their theoretical outlooks [20]. During World War II, many of them served as physicians in the army (R. Person, V. Gurfinkel, B. Khodorov). The majority of these scientists had obtained their MD during or after WWII, and could not find work till Stalin's death in 1953. Many of them were not skilled in foreign languages (Nikolai Alexandrovich spoke German, French, English, and knew Italian, Polish and Latin). Besides, foreign scientific literature was not easily accessible (Fig. 6).

Raisa Person, a pioneer in electromyography, recalled:

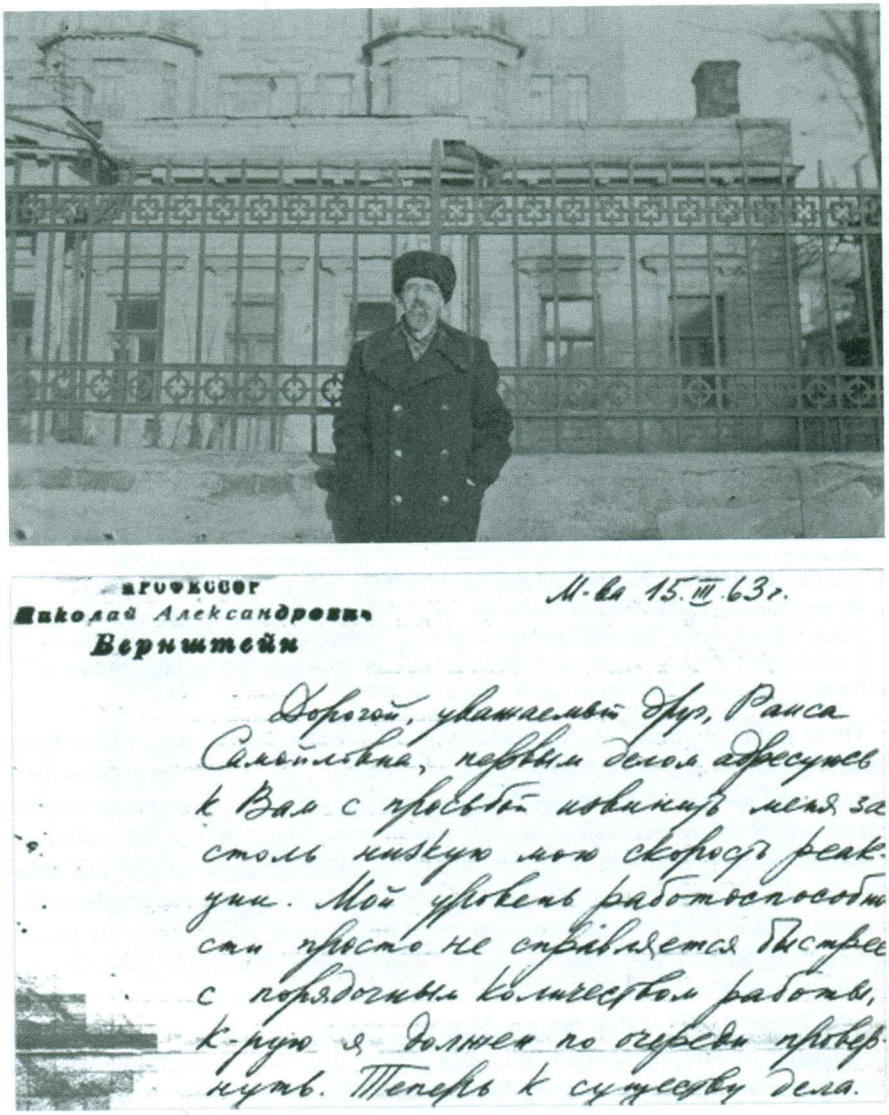
> ... Bernstein distanced himself from reflex theory, and did not consider reflex to be the basis of movement. He considered it to be just an element of movement having no principal significance in the organization of movement. He argued not so much with Pavlov, as with the conclusions made from Pavlov's experiments. The attempt to build the behavior of a living being on the basis of "conditional reflexes" was absolutely unacceptable to him. At that time, young physiologists started reading scientific literature published abroad, an advantage we had not had before. All we had was an incomplete translation of Sherrington into Russian, which we studied. In addition, very few people knew foreign languages. ... He was polite in an old-fashioned way. He used to address a person "My most honorable friend." For instance, he wrote to me: "My most honorable friend, Raisa Samuilovna, I inform you that my microreport will take place this Wednesday at the Institute of Neurosurgery (from an interview with Person, 2010).

These young physiologists, including Victor Gurfinkel, Mark Shik, Yakov Kotz, Raisa Person, Victor Lebedinsky, Vladimir Naidin, Iosif Feigenberg (who later became well-known) came to see Nikolai Alexandrovich to present their experimental results. Bernstein used to say: "If you have something to say, you can tell it in simple words" (from the interview with L.G. Okhnianskaya, 2010). His rehabilitation in science after 1953 went slowly. In 1957 Lyapunov's cybernetics seminars held at the Mechanics Department of the Moscow State University played an important role in this process [21]. At this seminar, Bernstein presented the lecture: "On the coordination of movement in humans and animals." In 1960, Norbert Wiener (1894–1964) came to Moscow, where he was introduced to Nikolai Alexandrovich who interpreted Wiener's public lecture at the Moscow State University. From the letter of N.A. Bernstein (12/XII, 1960), published in [10]:

> Here is some current information. Norbert Wiener came to Moscow. I was introduced to him during his lecture at the University. Together with A.R. Luria I interpreted his lecture and at the end we were exhausted, since the talk was very specialized and concerned strictly mathematical themes (phase spaces, theory of groups, rings and something else). We were sweating. Yet, he is a very nice and simple old man. I gave him a reprint of my article published in 1935 from the "Archive of Biological Sciences".

Norbert Wiener could now read the works of Nikolai Bernstein, who had already discovered many of his own ideas.

Approximately at the same time, Bernstein's ideas on motor control influenced Gelfand and Tsetlin's ideas on the non-individual control of multiple elements—a



профессор
Николай Александрович
Бернштейн

М-ва 15.III.63г.

Дорогой, уважаемый друг, Раиса Самойловна, первым делом обращусь к Вам с просьбой извинить меня за столь низкую мою скорость реакции. Мой уровень работоспособности сам просто не справляется быстрее с порядочным количеством работы, к-рую я должен по очереди проверить. Теперь к существу дела.

Fig. 6 *Above* Bernstein in Moscow. *Below* The letter of Bernstein to Person (courtesy of Person)

predecessor of the current "uncontrolled manifold" hypothesis developed by M. Latash and colleagues [12]. The seminar of the mathematician Israel Gelfand (1913–2009) and the physicist Mikhail Tsetlin (1924–1966) became the place where "biological mathematics was grown from inside out, drawing on the very essence of issues proposed by the life sciences".

The last years of Bernstein's life were a testament to his pupils. He wrote many introductions to the books of young authors, and references to their papers [22, 23].

In a paper published in 1962, Bernstein wrote: "It is possible to program an action with respect to a certain goal only based on an image or a model of a situation to which this action must lead and with respect to which the action is undertaken. However, since future events can be assessed or predicted only using probabilistic prognosis (a neat term by Feigenberg), it is clear that analysis of underlying physiological processes must be based on the theory of probabilities including its most recent developments" [22].

Victor Gurfinkel, who started his career under Bernstein's influence at the Moscow Institute of Prosthetic Appliances, has all his life till now elaborated the topic of tonus. What is the role of tonogenic structure—the background of all movement acts, the "bereitness" for the movement? Among Gurfinkel's most cited papers is an article about anticipatory postural adjustments (APA)—changes in leg muscle activity that anticipate arm elevation while standing [24].

In the 1935 paper "The Problem of Interrelation Between Coordination and Localization" [15], Bernstein wrote about movement anticipation: "At the moment when movement begins there is already present in the central nervous system a whole collection of engrams that are necessary for the movement to be carried out to its conclusion." In part due to Bernstein's early work on motor preparation, tonus is now viewed as an anticipatory physiological adaptation and organization of the periphery.

Bernstein's ideas about tonus inspired many experimental studies of the pre-tuning of movement [25–27]. The task of voluntary bimanual unloading is a good example of such a "local" synergy [25, 26]. When a subject removes a weight from his forearm using the contralateral arm, the unloaded forearm maintains an almost stable position in space ("barmen effect") due to the reduction of ipsilateral biceps activity prior to the unloading. Anticipatory postural adjustments consist here of changes in the activity of a forearm flexor muscle prior to active unloading of the limb and act to stabilize the forearm angular position (Fig. 7). To evaluate the role of motor cortex and the pyramidal system in the anticipatory postural adjustment to forearm unloading, we investigated the motor potentials (MEPs) evoked by trans-cranial magnetic stimulation (TMS) in a forearm flexor at the time of bimanual unloading [25]. On the other hand, if the unloading is triggered via electromagnet by lifting an equal weight by the other arm, the anticipatory postural adjustment is learned through the repetition of unloading (three series of 20 trials). During learning the amount of EMG depression increased and this depression became better synchronized with the time of unloading. Even though the unloading profiles were similar at the beginning and at the end of learning sessions, practice resulted at the final stage of learning in less elbow flexion after the unloading due to anticipatory biceps activity depression [27].

What references did Bernstein make to movement anticipation in his experimental material and interpretations? In 1939 he said: "Our analysis of virtuoso pianists' movements showed that at fast tempos muscles-flexors of forearm and hand take over the muscles-extensors early in the midstream of the extension, almost in the middle of it, and stop functioning in the middle of its subordinate flexion movement" [28]. The relation between tuning and motor commands is

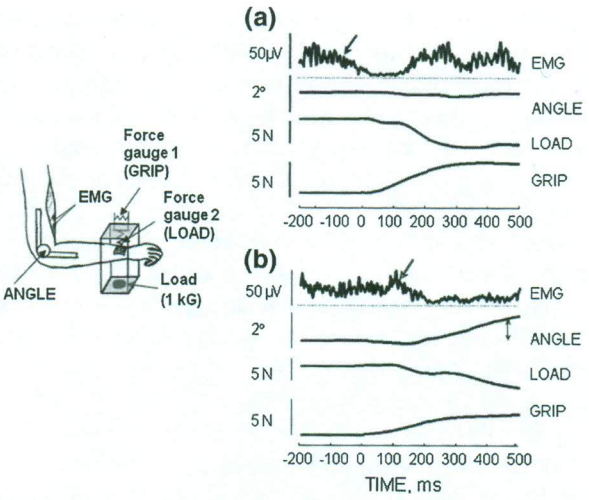


Fig. 7 Active (**a**) and passive (**b**) unloading. *Left*, schemes of the experiment. *Right*, time course of the EMG of m. biceps, elbow angle, load force, and handle grip force. In the time scale, zero corresponds to the touching of the handle. Note that in active unloading the EMG change precedes the onset of movement (t = 0), whereas in passive unloading the EMG decreases after t = 0 [25]

illustrated by the example, given by Bernstein, of a violinist compressing a string with his finger. That compression does not create sound by itself but specifies which sound will be elicited by the next stroke of the bow [29]. (The contribution to this volume by Ito [30] and Nadin [31] make reference to some of Bernstein's ideas.)

Nikolai Alexandrovich Bernstein died on 16 January 1966. No officials came to his funeral. After his death his disciples published a book with their collective work, dedicated to their teacher [32]. Their interdisciplinary seminars produced a generation of outstanding researchers. Among the achievements of this generation are the discovery of the spinal stepping automatism in the cat [33], "equilibrium point (EP) hypothesis" [34], the hindlimb wiping reflex of the frog as an example of a targeted trajectory organized at the spinal level [35], and the probabilistic prognosis in human activity [15]. The author of the EP hypothesis, Anatol Feldman, whose scientific career began in Gelfand's seminar, said (from the interview in 2011):

> In my opinion, the most important contribution of Bernstein's legacy is the problem of the redundant degrees of freedom of the motor apparatus. When we make a movement, a lot of joints are involved. The question is: how does the system cope with it? The goal is sometimes described very simply: to reach a certain point in a space having only 3 coordinates. If we add the orientation of the object that we want to catch, there are 6 coordinates; however, the degrees of freedom of the involved joints are much larger…Bernstein formulated significant questions in motor control science. The idea of motor equivalence (like, for instance, the variability of the movement of the hammer relative to the consistency of the final point) is very important for me. It is directly related to the problem of redundant degrees of freedom… Also, Bernstein made conclusions on and summarized for us what had been done before. I must point out that the mathematician Israel Moiseevich Gelfand used to say that Bernstein had a mathematical mind, and that Bernstein's style of thinking

was similar to his. We are all pupils of Bernstein. His ideas were to some extent reflected in the ideas that Gelfand and Tsetlin generated, for instance, the idea of "non-individualized" control of many motor elements. I can see how these ideas are related to the modern understanding of "non-individualized" control of many muscles and joints…The Moscow School of Movement Physiology created by Gelfand carried a charge received from Bernstein. Bernstein's approach influenced their style of thinking that prompted us not to solve local questions, but to try and understand how the brain controls movements. Let's take, for instance, the so-called "cat locomotion". The research was initiated (perhaps subconsciously) by the idea that a big number of elements can be controlled relatively simply. Eventually, such a locomotor area was found by Mark Shik, Gregory Orlovsky, and Fedor Severin. This locomotor area could be tonically stimulated to induce locomotion of the decerebrated cat. By enhancing stimulation, we can change the speed of movement and make the cat change walking to galloping.

Mark Shik, discoverer of locomotor center in cats, comments on the ideas of Bernstein (from the interview with Shik, 2010):

It is difficult to imagine how unusual his ideas were. The thing is that the anatomists had already known, for about 100 years or so before Bernstein, that CNS consisted of different parts: spinal cord, brain stem, pons, mesencephalon…But only Bernstein came to think – whether suddenly or over time, I don't know – that, if the nervous system functioned on different levels, each of which had its own methods of control, movement control could also be regarded as a multilevel system. As far as I know, nobody cared to exploit these facts – that the anatomists had long known – in order to understand movement physiology. It was a real revolution, a revelation. He brought the whole movement physiology to a new level. There were studies in movement physiology before Bernstein. Physiologists have been interested in movement for a long time, starting from the Middle Ages. But the idea that movement has a multilevel nature and every level of CNS performs its own part and controls movements in its own way was novel. It greatly impressed me. Neuro-pathologists as well as neuro-anatomists have known for a long time that local lesions in different locations of the brain have specific symptoms and signs. Yet, I have never heard about any neurologists who would have developed a global model based on these facts. Nikolai Bernstein created a whole system. He initiated, so to speak, a structured approach to studying movement physiology.

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References

1. Agarwail, G.C., Gottlieb, G.L.: Control theory and cybernetic aspects of motor systems. In: Whiting, H.T.A. (ed.) Human Motor Actions: Bernstein Reassessed. North-Holland, Amsterdam (1984)
2. Latash, L.P.: Automation of movements: challenges to the notions of the orienting reaction and memory. In: Latash, M.L. (ed.) Progress in Motor Control, vol. 1: Bernstein's Traditions in Movement Studies, pp. 51–88. Human Kinetics, Champaign (1998)
3. Sirotkina I.E.: Outstanding Physiologist. Classic of psychology? (On 100 years of birthday of NA Bernstein). J. Psych. **5**,116–127 (1996). (in Russian)
4. Bernstein S.A.: Early years, v.1,2. Family Archive of A.S. Bernstein (1945). (in Russian)

5. Feigenberg, I.M.: Nikolai Bernstein—from reflex to the model of the future. Moscow, Smisl (2004), translated into English in Feigenberg I.M. LIT Berlin, in Press (in Russian) (2014)
6. Kruglyanskaja, N.A. (ed.): Popovs, The Cloth-Makers: Notes About Moscow Life and Not Only. Russki Put', Moscow (2010). (in Russian)
7. Jansons, H.: Bernstein: the microscopy of movement. In: Cappozzo, A., Marchetti, M., Tosi, V. (eds.) Biolocomotion: A Century of Research Using Moving Pictures, pp. 137–174. Promograph, Roma (1992)
8. Popova, T.S., Mogil'anskaya, Z.V. (with participation of Bernstein N.A., edited by Bernstein N.A.): Techincs of Motion Study, Practical Handbook on Cyclogrammetry. Moscow-Leningrad (1934). (in Russian)
9. Bernstein, S.A.: Selected Works on Structural Mechanics, p. 451. Gosstroiisdat, Moscow (1961). (in Russian)
10. Chkhaidze L.V., Chumakoff S.V.: The Formula of Stride. Moscow (1972). (in Russian)
11. Bernstein, N.A.: Die Kimozyclographische Methode der Bewegungsuntersuchungen. In: Abderhalden E. (ed.) Handbuch der biologischen Arbeitsmethoden, vol. 5. pp. 629–680 (1928). (in German)
12. Latash, M.L.: Synergy. Oxford Press, New York (2008)
13. Gurfinkel, V.S., Cordo, P.J.: The scientific Legacy of Nikolai Bernstein, In: Latash, M.L. (Ed.), Progress in Motor Control, Vol. 1: Bernstein's Traditions in Movement Studies, pp. 1–19. Human Kinetics, Champaign (1998)
14. Bernstein, N.A.: Contemporary studies in the physiology of the neural process. Feigenberg, I.M., Sirotkina, I.E. (eds.) Moscow Smisl, 328 p. (in Russian) (2003). (See review of this book by Latash M.L. A New Book by Nikolai Bernstein: Contemporary Studies in the Physiology of the Neural Process, Motor Control, 10, 1–6, 2006)
15. Bernstein, N.A.: The problem of the interrelation of co-ordination and localization. Arch. Biol. Sci. **38**, 1–34 (in Russian) (1935), translated into English in Bernstein, 1967 (The Coordination and Regulation of Movements. Pergamon Press, 196 p), in German in 1975 (Bewegungsphysiologie von N.A. Bernstein. Hrsg. Von L. Pickenhein und G. Schnaber, Leipzig, Barth, Bd.9, 260 s.)
16. Wiesendanger, M.: Bernstein's principle of equal simplicity and related concepts. In: Latash, M.L. (Ed.) Progress in Motor Control, Vol. 1: Bernstein's Traditions in Movement Studies, pp. 1–19. Human Kinetics, Champaign (1998)
17. Turvey, M.T.: Coordination. Am. Psychol. **45**, 938–953 (1990)
18. Latash, M.L., Turvey, M.T. (eds.): Dexterity and its Development (with "On Dexterity and its development" by N.A, Bernstein). Erlbaum, Mahwah (1996)
19. Stuart, D.G.: Integration of posture and movement: contribution of Sherrington, Hess and Bernstein. Human Mov Sci **24**, 621–643 (2005)
20. Talis, V.L., Feigenberg, I.M.: Nikolai Alexandrovich Bernstein and the Moscow Motor Control School in the Late Sixties. Soc Neurosci Abstr. **40**, 17– 21 (2010)
21. Smoljaninov, V.V.: From the biomechanics to the physiology of action (the scientific school of NA Bernstein). In: Proceedings of the Conference "Technologies of Informatisation in Professional Activity", Izhevsk, 10–14 Nov 2008. (in Russian)
22. Bernstein, N.A.: New lines of development in contemporary physiology. The materials of the conference of the Institute of the Labor Hygiene, pp. 15–21 (1962). (in Russian)
23. Bernstein, N.A.: On the perspective of mathematics in biocybernetics. The foreword to the book of V. Shernish, A. Napalkov "The Mathematical Apparatus of Biological Cybernetics". Moscow Medicine, p. 3–30 (1964). (In Russian)
24. Belenkii, V.Y., Gurfinkel, V.S., Paltsev, E.I.: On the control elements of voluntary movements. Biofizika **12**(1), 135–141 (1967). (in Russian)
25. Kazennikov, O., Solopova, I., Talis, V., Grishin, A., Ioffe, M.: TMS-responses during anticipatory postural adjustment in bimanual unloading in humans. Neurosci. Lett. **383**, 246–250 (2005)
26. Paulignan, Y., Dufosse, M., Hugon, M., Massion, J.: Acquisition of co-ordination between posture and movement in a bimanual task. Exp. Brain Res. **77**, 337–348 (1989)

27. Kazennikov, O., Solopova, I., Talis, V., Ioffe, M.: Anticipatory postural adjustment: the role of motor cortex in the natural and learned bimanual unloading. Exp. Brain Res. **186**, 215–223 (2008)
28. Bernstein, N.A: Modern data on the structure of neuro-motor process. In: For the Musical Pedagogue, pp. 207–231. Moscow, Muzgiz (1939). (in Russian)
29. Baader, A.P., Kazennikov, O., Wiesendanger, M.: Coordination of bowing and fingering in violin playing. Cogn. Brain. Res. **23**(2–3), 436–443 (2005)
30. Ito, J.P.: Repetition without repetition: how bernstein illumines motor skill in muscle performance. In: Nadin, M. (ed.) Anticipation: Learning from The Past. Springer, Cham, Switzerland (2015)
31. Nadin, M.: Variability by another name: "repetition without repetition." In: Nadin, M. (ed.) Anticipation: Learning from The Past. Springer, Cham, Switzerland (2015)
32. Gelfand, I.M., Gurfinkel, V.S., Fomin, S.V., Tsetlin, M.L.: Models of the Structural-Functional Organization of Certain Biological Systems. Academy of Science of the USSR, Moscow (in Russian) (English translation by C.R. Beard and edited by J.S. Barlow, Boston: MIT Press) (1971)
33. Shik, M.L., Orlovsky, G.N.: Neurophysiology of locomotor automatism. Physiol. Rev. **56**(3), 465–501 (1976)
34. Asatryan, D.G., Feldman, A.G.: Functional tuning of the nervous system with control of movement or maintenance of a steady posture: i. mechanographic analysis of the work of the limb on execution of a postural task. Biophysics **10**, 925–935 (1965)
35. Fukson, O.I., Berkinblit, M.B., Feldman, A.G.: The spinal frog takes into account the scheme of its body during the wiping reflex, Science **209**(4462), 1261–1263 (1980)