

# Biomechanics for Instructors

Nikolai Aleksandrovich Bernstein

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Translated by Rose Whyman

 Springer

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Translated by Rose Whyman with an introductory essay by Vera L. Talis. This book was first published in Russian by Novaya Moskva in 1926 as a set of lectures for courses for instructors in the industrial-economic subdivision of Moscow Professional Training.

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*For Brian Door, as ever, with all my love  
and thanks.*

## Preface

I hope this translation of Bernstein's *Biomechanics for Instructors* will be of interest to people involved in a wide range of research and practice. It must be said that this set of lectures was developed and published in the 1920s, and N.A. Bernstein conveyed the state of biomechanics as it was known at that time. However, as is the case with any science, knowledge has advanced. Readers are encouraged to expand their study in this field by reviewing the latest findings in the biomedical literature and current textbooks in order to place Bernstein's explanations in the context of current knowledge. This is especially important with respect to discussions of physiology—whether humans or animals—as knowledge in this field has grown substantially over the last century.

This proviso does not diminish the significance of these lectures and Bernstein's work in general, which, as Vera Talis explains in the introductory essay, is far from being fully acknowledged or assessed. She details much of the valuable work that has been carried out by others but does not mention the tremendous work she herself has done to preserve Bernstein's legacy. Hopefully, her book *Doktor kotoryi lyubul parovoziki (The Physician Who Loved Steam Engines)* will soon be in print and much more information about Bernstein's life and work will be available to a general readership. Also, to date there has been a lack of recognition of how Bernstein's research impacted in fields beyond that of biomechanics and neurophysiology. He was influential in Soviet sport and athletics training, and much research into this influence and its impact on the development of skill and virtuosity in this area remains to be done.

In drama, dance and theatre work, we are beginning to understand his influence in his time and the significance of Bernstein's discoveries about movement in the period of emergence of the Free Dance Movement at the beginning of the twentieth century on which cultural historian Irina Sirotkina has carried out extensive and groundbreaking research, resulting in many articles and the 2012 book *Svobodnoye Dvizheniye i Plasticheskii Tanets v Rossii*, Moscow: Novoye Literaturnoye Obzreniye.

Irina Sirotkina's and science historian Roger Smith's *The Sixth Sense of the Avant-Garde Dance, Kinaesthesia and the Arts in Revolutionary Russia* (2017)

includes discussion of Bernstein's work to show how significant movement and the sense of movement were to pioneers of modernism at the turn of the twentieth century, in revolutionary Russia and beyond.

Irina's *Mir Kak Zhivoe Dvizhenie- intellektual'naya biografia Nikolaya Bernshteina* (Moscow: Kogito-Tsentr 2018) is a further important contribution.

My own research encompasses the work of the world-famous theatre directors K.S. Stanislavsky and V.E. Meyerhold, and I am currently investigating how Meyerhold and others including the film director Sergei Eisenstein developed actor-training systems which they called Biomechanics and connections between these, and biomechanics. What is clear is that Bernstein's insight into the science of movement was profound, and a clearer understanding of this, prevented as Bernstein's persecution began, as described in the introductory essay would have been of use in actor training then and could be of great use in developing the practice of performer training today.

Finally, I would like to mention that I first heard of Bernstein during my training with the Professional Association of Alexander Teachers. In our studies of Movement Science, my teacher Brian Door introduced us to *The Co-ordination and Regulation of Movements*. My aim is to contribute to the preservation of the Alexander Technique as I have been taught it through my research and practice and in this the opportunity to work on Bernstein continues to prove an inspiration and a privilege.

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# Introduction

Nikolai Bernstein (1896–1966) was a Russian scientist, the author of the theory of construction of movements in humans and animals. According to this theory, coordination of movement is organised hierarchically, with many levels, and motor learning is a process of transitioning a specific movement to the control of the appropriate level. Bernstein, who was a physician, a specialist in mechanics and a mathematician, proposed an entirely original definition of the coordination of movement as the central nervous system's process of overcoming the redundant number of degrees of freedom of the movement apparatus in humans. The theses he developed about the role of the central command and sensory corrections through the reflex circle have become the basis of contemporary motor control theory. (As a young contemporary of Ivan Petrovich Pavlov (1849–1936), Bernstein criticized the application of Pavlov's reflex theory in a simplified way to living movement, where muscle contraction is initiated by the reflex arc from external stimuli. Elaborating the 'physiology of activity' throughout his life, Bernstein showed that any living motion is initiated from within the organism through the reflex circle, where the central neural system can get feedback about movement realization.)

Up until now, two of Bernstein's books have been translated into English. The first, *The Co-ordination and Regulation of Movements*, was edited by Bernstein himself and published in 1967, a year after his death.<sup>1</sup> The second book, *O Lovkosti i ee Razvitiu* (*On Dexterity and its Development*), is a popular interpretation of his major book, *O Postroenii Dvizhenii* (*On the Construction of Movements*), for which Bernstein was awarded the Stalin Prize for science in 1948. In 1949, soon after finishing *On Dexterity and Its Development*, Bernstein began to be persecuted. For this reason the book was not published during his lifetime. A proof copy was discovered after Bernstein's death by his student and first one of his biographers I.M. Feigenberg and was published in 1991. In 1996, *On Dexterity and Its Development* was translated into English and published with extensive commentaries

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<sup>1</sup> Bernstein, NA (1967) *The Co-ordination and Regulation of Movements*. Oxford, Pergamon Press.

by the distinguished American scientists Mark Latash and Michael Turvey.<sup>2</sup> From the centenary of Bernstein's birth in 1996 to 2000, many papers by Bernstein and his co-authors were translated and published with commentaries in the journal *Motor Control*. Before you now is the translation of Bernstein's third book, *Biomechanics for Instructors*, which is a popular version of his book of 1926, *Obshchaya Biomekhanika (General Biomechanics)*.

*Biomechanics for Instructors* is a clear, seemingly simple description of the structure of the human body as a machine. It is an entertaining story, presented from an evolutionary point of view, about how the muscles work, how the skeleton is constructed and how the joints move.

The book is unique in that we have the opportunity to 'hear' live dialogue between Bernstein and students, his pedagogic technique and his way of conveying the difficult questions of mechanics. (Only a few two-minute long documentary films of Bernstein, broadcast in 1948, which were shown before the main feature in cinemas are known of today.) *Biomechanics for Instructors*, which has been republished several times in Russia,<sup>3</sup> began to interest the translator, Rose Whyman, although her speciality is far removed from biomechanics and the physiology of movement. In studying stage movement and how the Alexander Technique can facilitate this, Rose could see answers in Bernstein's book to her practical questions about the structure of the human body, the working of its muscles and how the joints are stabilised. She could also see the book as a popular interpretation of complex questions of the control by the brain of the human movement apparatus.

It must be emphasized that translating Bernstein's texts is complicated because of vividness of his speech and his rather creative word formations. He sometimes uses clauses that last the length of a whole paragraph (!), and correspondingly, there is a great concentration of thought within them. *Biomechanics for Instructors* is written in a relatively easy style, in the form of a dialogue with the auditorium, with speech that is at times simple, colloquial and every day, including archaisms, and the translator has dealt splendidly with this, preserving the very spirit of the times.

The mid-1920s in Russia was a time when a mass of young, poorly educated people poured into industrial and cultural life as a result of the changes to society after the October Revolution of 1917. It was also a time when a great number of educated and well-off people left Russia and it became a time of challenge for those remaining. Nikolai Bernstein's father, Aleksander Nikolaevich Bernstein, the well-known Moscow psychiatrist, a student of the famous S. S. Korsakov,<sup>4</sup> founded *Tsentrāl'nyi Preemniĭ Pokoi* (The Central Hospital Ward). This was the first clinic in Moscow where mentally ill people were kept without restraints. Aleksander's

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<sup>2</sup>Latash, ML, Turvey, MT (Eds.) (1996) *Dexterity and Its Development*. Mahwah, NJ, LEA Publishers.

<sup>3</sup>Bernstein, NA (2001) *Biomekhanika dlya Instruktorov (Biomechanics for Instructors)* In Shestakov MP (Ed.) *Izbrannie trudi po biomekhanike i kibernetike (Selected works on biomechanics and cybernetics)* Moscow, SportAcademPress. [In Russian].

<sup>4</sup>Sergei Sergeevich Korsakov (1854–1900) was one of the greatest neuro-psychiatrists of the 19th century, author of works in neuropathology, psychiatry and forensic medicine.

work was inspired by the psychiatry of his time, where in both Europe and Russia experimental scientific approaches to diagnostics were being developed and at the same time that there was progress in treating mentally ill people more humanely.<sup>5</sup>

After the Revolution, Bernstein senior became the deputy head of the Main Administrative Board of the Scientific Institutions of the Academic Center of Narkompros.<sup>6</sup> He worked in the Commission for Reform of Medical Education and in 1920 founded, and became director of, the Moscow State Psychoneurological Institute.

The close relationship and the influence of his father on Nikolai Bernstein is evident in their correspondence of 1914, when the 18 (!) year old son, entering the historical-philological (!) faculty of Moscow State University, wrote to his father 'I found an essay about Gogol<sup>7</sup> in Korolenko,<sup>8</sup> where he expresses the same proposition about his cyclothymia<sup>9</sup> as you and refers to Bazhenov's 1902 essay, which you perhaps know.<sup>10</sup> He points out that Gogol's father suffered from the specific features of the very illness that you have described; the alternating periods of feverish activity, the inventiveness, which coincides with manifestations of his comic talent and other times of dark depression, apathy and a horror of death, from which, it would appear, he died'.<sup>11</sup> The characteristics of this letter—punctiliousness in citation, a particular feeling for words and a psychological aspect to the scientific approach—are remarkable in Nikolai Bernstein's work throughout his life. It is a great sadness that these qualities of the brilliant scientist were later used against him, when at the end of the 1940s in Russia he was stigmatised for 'cosmopolitanism' because of his citations of foreign authors and for 'idealism' at the expense of 'materialism' because of the figurativeness of his comparisons. It is surprising but the ideas expressed in the letter from 1914 quoted above were ideas that persisted through

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<sup>5</sup> See Gilyarovskiy, VA (1922) Pamyati A.N. Bernsteina (A.N. Bernstein Obituary). *Zhurnal Psikhologii, Nevrologii i Psykhiatrii* (Journal of Psychology, Neurology and Psychiatry) 1, pp. 5–9. [In Russian].

<sup>6</sup> *Narodnyi Kommissariat Prosveshchenie* (The People's Commissariat for Education), *Narkompros*, was the Soviet agency for administration of public education and culture.

<sup>7</sup> Nikolai Vasilievich Gogol (1809–1852) was the great Russian writer famous for works such as the novel *Myortvye Dushi* (*Dead Souls*) and the play *Revizor* (*The Government Inspector*).

<sup>8</sup> Vladimir Galaktionovich Korolenko (1853–1921) was a Russian writer, journalist and human rights activist. The essay referred to is Korolenko, V.G. (1909) 'Tragediya velikogo yumorista: Nieskol'ko myslei o Gogol'e' ('The tragedy of great humanist: several thoughts about Gogol'). *Russkoye Bogatstvo* (Russian heritage), 4, 6. p. 27. [In Russian].

<sup>9</sup> Cyclothymia is now referred to as bipolar disorder.

<sup>10</sup> Nikolai Nikolaevich Bazhenov (1857–1923) was a Russian psychiatrist, who worked for the humane treatment of mentally ill patients. In 1916 he emigrated first to France then returned to Russia from Belgium in 1923 when he was very ill. The essay referred to is Bazhenov, NN (1902) *Bolezni i smert' Gogolya* (The Illness and Death of Gogol). Public reading at the annual meeting of The Moscow Society of Neuropathologists and Psychiatrists. Kushnerev@K, b. 1, p. 38. [In Russian].

<sup>11</sup> Talis, VL (2019) *Doktor kotoryi lyubil parovoziki* (*The Physician Who Loved Steam Engines*). Manuscript. [In Russian].

Bernstein's life, as one of his final notes in 1965 in the popular journal *Science and Life* is entitled 'Death from the fear of death'.<sup>12</sup>

After Bernstein entered the historical-philological faculty of Moscow State University, he transferred to the medical faculty, moved by a patriotic desire to take part in the First World War, which was just beginning. After he graduated from the University he served as an army doctor in the Red Army from December 1919 to March 1921. After demobilisation, he came to the Psychoneurological Institute where he headed the laboratory until 1922 and published his first work in 1922.<sup>13</sup> This publication appeared in the first issue of the journal founded by his father and was an obituary to A.N. Bernstein who died aged 52 in May 1922, at the peak of his creative energies. In August of the same year N.A. Bernstein had moved to the famous *Tsentralnyi Institut Truda* (TsIT), Central Institute of Labour, established on the personal instruction of V.I. Lenin.<sup>14</sup> In summer 1924, Bernstein was already presenting, as a member of the TsIT delegation at the First International Congress on the Scientific Organisation of Labour in Prague, the results of registering the movement of humans by his own method of cyclogrammetry (see Lecture 8 in this book). In 1926, he wrote his first book, *General Biomechanics*, dedicated to the memory of his father. The founder and leader of TsIT was Aleksei Kapitonovich Gastev, a metal worker from the Russian city of Suzdal, a revolutionary, poet and later on a victim of Stalin's repressions, shot in 1939. We gain an insight into the atmosphere of those years from his poem:

LET US ERECT A MONUMENT  
TO THE AMOEBA—the creator of reaction,  
TO THE DOG—our greatest friend,  
    called to exercise.  
TO THE MONKEY—the hurricane  
    of living movement,  
TO THE HAND—the wonderful  
    intuition of will  
    and construction,  
TO THE BARBARIAN with his stone  
    strike,  
TO THE INSTRUMENT,  
    as the banner of will,  
TO THE MACHINE—teacher  
    of accuracy and speed  
and TO ALL BRAVE HEARTS,  
calling for the REMAKING OF HUMAN BEING.

<sup>12</sup>Bernstein, NA (1965) Smert' ot stracha smerti [The death from the fear of death]. *Nauka i Zhizn'* (*Science and Life*) 2, p.149 (1965). [In Russian].

<sup>13</sup>Bernstein, NA (1922) K voprosu o vospriyatii velichin (o roli pokazatel'noi funktsii v prozessakh vospriyatiiya velichin) (On the question of the perception of quantities (about the role of exponential function in the processes of the perception of qualities)). *Zhurnal Psikhologii, Nevrologii i Psykhiatrii* (J of Psychology, Neurology and Psychiatry) 1, p. 21–54. [In Russian, abstract in German].

<sup>14</sup>Vladimir Ilyich Ulyanov (1870–1924), better known as Lenin, the head of the government of Soviet Russia from 1917 to 1922 and of the Soviet Union from 1922 to 1924.

CURSED be all  
 cowards,  
 hypocrites,  
 obscurantists,  
 those who howl and shriek  
 on the roads  
 and in marketplaces  
 where our machine races along.  
 HELLO!  
 Hello to our happily  
 dashing our  
 IRON,  
 FULL-BLOODED,  
 SURE  
 MONTAGE!<sup>15</sup>

*Biomechanics for Instructors* came out in 1926 after N.A. Bernstein left TsIT, seemingly because of the incompatibility of the ‘romantic’ proletarian approach of Gastev with the academic approach of Bernstein, a third generation physician and scientist. His sceptical attitude to TsIT is evident at the beginning of Lecture 10 in this book, where we read: ‘the research that I carried out on labour movements in TsIT ceased after my resignation...’ TsIT, which was set up to be self-financing, not only carried out research but also trained workers. In Lecture 10 a member of the student audience notes, ‘The lads who have trained at TsIT were also told to chop within a single plane but then you do not get the force. If you take it out from the body, it is somehow easier’. Including this wonderful example of ‘simple-hearted’ speech (most likely having invented it himself), Bernstein begins to compare the ‘vertical’ strike in chiselling, which was taught at TsIT and the strike ‘to the side’. In recounting the example of the strike ‘to the side’, which gives the most force to the strike and which was later on to be a classic of the physiology of movement, the 29-year-old lecturer exclaims rhetorically:

Is it possible then that all vertical strikes are so hopelessly bad? Regrettably this is so. Is it possible then that all the strikes to the side are irreproachably good? Well, no, it is impossible to say that. I shall reveal a little secret to you. I have shown you all kinds of vertical strikes and I have chosen only the best of those to the side that came out as a result of detailed investigations.

In this way, having revealed a little of the principles of experimental work of the time which still apply in the present day, Bernstein displays his unique ability to see the most characteristic features of living movement visually without the statistics in use today. In fact Fig. 6 in this book becomes the first experimental figure in his main book, *On the Construction of Movements* (1947), illustrating his idea that:

cases when, during a specific movement, very different muscle groups are activated at different times and in different patterns, as compared to what could be expected from elementary anatomical analysis, are much more common than cases when muscle action is classical

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<sup>15</sup>Gastev AK (1973). *Trudoviye ustanovki* (Organization of labour) in Gastev Yu.A., Petrov E.A. (Eds.) *Trudoviye Ustanovki*, Moscow, Ekonomika. [In Russian].

and fully understandable. There are many movement elements, where we are still unable to interpret the behavior of each muscle group; sometimes, analysis of external and reactive forces can be performed and it clearly reveals the logic of those unexpected at the first glance muscle actions, but this logic is very much different from the elementary logic of high-school textbooks.<sup>16</sup>

Lecture 6 is dedicated to efficient stance in labour movements, and here the audience pose themselves the question of ‘which angle between the feet is more correct in filing and chopping—67 or 70 degrees?’ The answer is:

Perhaps the extent to which all these values and proposals are random and groundless is not as evident to you as it is to me, from my perspective. These values are often just spun out of thin air to give some firm rule and expound how scientific one’s approach to the question is.

After this astonishing observation (which is still relevant today!), Bernstein, having defined the motion of the hammer in the strike, evaluates the corresponding movement of the common centre of gravity of a worker with a hammer in their hands and, having clarified that, concludes for effect that ‘Obviously, all the debates about 67 and 70 degrees completely fall away’.

It must be noted that as in *Lectures on Biomechanics for Instructors*, all Bernstein’s further experimental and even theoretical work has a clear practical application, whether it is the calculation of moments of force in running with highly professional sports people or the force of strikes on the piano. In this way ‘the investigation and improvement of the working place of the tram driver’ of 1928 becomes in 1934 ‘the project of the efficient work place of the metro driver’.<sup>17</sup> On leaving TsIT in January 1925, Bernstein began a study of the biodynamics of strikes on the piano in the Gosurdarsvennyi Institut Muzykalnykh Nauk (The State Institute for Musical Sciences), which has the evocative acronym ‘GIMN’.<sup>18</sup> Among the colleagues who went with him from TsIT to GIMN was Tat’yana Sergeevna Popova (1902–1992), the wife of his younger brother, Sergey.<sup>19</sup> Tat’yana Sergeevna, who was educated in the mathematical faculty of Moscow State University, came from a millionaire merchant family of clothing manufacturers—the Popovs. She, like another member of this family, the famous avant-garde painter Lyubov Sergeevna Popova (1889–1924), was without doubt one of the most outstanding figures of her time. In 1924, in the period of work at TsIT, she writes:

The Central Labour Institute 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

<sup>16</sup>Bernstein NA (1947). *O Postroenii Dvizhenii (On the Construction of Movements)*, Moscow, Medgiz, p.24. [In Russian].

<sup>17</sup>Autobiography of NA Bernstein of 29.05.1945 from the personal files of NA Bernstein in the Archive of Medical Science, Moscow (F. 9120. V. 8/3. Unit 19).

<sup>18</sup>The acronym GIMN spells the word for ‘hymn’ in Russian.

<sup>19</sup>Sergei Alexandrovich Bernstein (1901–1958) was a professor of structural mechanics, author of fundamental calculation and trials of engineering constructions.

studies mostly the work of a metalworker and his two main procedures: chiselling and filing.<sup>20</sup>

The study of movements of musicians is an area that still has been studied little in spite of the great interest in it,<sup>21</sup> because of the methodological and experimental complexities of the registration and interpretation of the subtle highly coordinated movements involved. Bernstein entered this area as a musician with absolute pitch, having composed music and played professionally on the piano and oboe. According to legend in the Bernstein family, Rachmaninov prophesied a career in music for him.<sup>22</sup> In the essay ‘Research on the Biodynamics of the Piano Strike’ of 1930, Bernstein and Popova write that ‘most studies in the area of piano methodology originate either from physiologists who are dilettantes in music or from musicians who know nothing about physiology’. This essay, translated in 2003, is introduced by the following words; ‘Bernstein and Popova report an impressive study (even by modern standards) of a complex motor behaviour: movements performed by concert pianists, specially a series of octave strikes made with one hand’.<sup>23</sup>

In the years 1927 to 1933, the work of Bernstein and his colleagues was often published in German in the journal *Arbeitsphysiologie (Labour Physiology)*. From the 1930s, the work of Bernstein and his colleagues was in the main devoted to the biodynamics of locomotion—walking, running, jumping with a run up and so on. It is interesting that the investigation of locomotion began initially at the behest of Narodnyi Kommissariat Putei Soobshcheniya (The People’s Commissariat for Railways), and the first paper was published in 1926 in the collected articles of *Voprosy Dynamiki Mostov (Questions of the Dynamics of Bridges)*.<sup>24</sup> Later Bernstein’s group studied ‘normal walking, loaded walking, changes in walking due to tiredness and in the restoration period, age-related changes to walking (children’s walking development, elderly gait), gait in amputees with prosthetics, central-nervous pathology of walking, the running of outstanding sportsmen, the development of running in children, the technique of the long jump with a run up etc.’<sup>25</sup> In mid-September 1929, Nikolai Bernstein took abroad a description of human walking

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<sup>20</sup>Talis VL (2015) ‘New pages in the biography of Nikolai Alexandrovich Bernstein’ in Nadin, M. (Ed.) *Anticipation: Learning from the Past. The Russian/Soviet Contribution to the Science of Anticipation*. Cham, Springer, p. 313–328.

<sup>21</sup>See, for example, Altmüller, E, Wiesendanger, M., Kesselring, J. (Eds.) (2006) *Music, Motor Control and the Brain*. Oxford, Oxford University Press.

<sup>22</sup>Rachmaninov, Sergei Vasilevich (1873–1943) was a Russian composer and virtuoso pianist. Following the Russian Revolution, Rachmaninov and his family left Russia; in 1918, they settled in the United States.

<sup>23</sup>Kay, BA, Turvey, MT, Meijer, OG (2003). ‘An Early Oscillator Model: Studies on the Biodynamics of the Piano Strike (Bernstein and Popova, 1930)’, *Motor Control*, 7, p. 1–24.

<sup>24</sup>Bernstein NA (1927) ‘Issledovaniya po biodynamike khod’bi i bega’ (Studies on Biodynamics of Walking and Running) in *Sbornik: Voprosy Dynamiki Mostov, trudi Narkomata Putei Soobsheniya*, (Collected Works: *Questions of the Dynamics of Bridges. Works of The People’s Commissariat for Railways*) Vol.63, p.51–76.

<sup>25</sup>Autobiography of N.A. Bernstein of 29.05.1945 from the personal files of N.A. Bernstein in the Archive of the Russian Academy of Medical Science, Moscow (F. 9120. V. 8/3. Unit 19).

in the form of an atlas, hoping that Springer would publish it. When the plans for publication fell apart he left *The Atlas of Human Walking* as a gift for the Dortmund Institute of Labour before his departure to Moscow at the beginning of January 1930.<sup>26</sup>

Bernstein's trip to France and Germany (for about 3 months at the end of 1929) was dedicated, on the one hand, to the buying and ordering in Europe of experimental equipment for the Moscow laboratories and, on the other, to instructing his European colleagues in his technique of recording movements, which was advanced for the time. The head of the Russian physiological school, an academician from a Russian aristocratic family, Alexei Alexeevich Ukhtomsky writes:

A young Russian scientist N.A. Bernstein showed the striking example of how Fischer's method can be used for the complete mechanical assessment of various movements in the process of physical labor ... Having registered the trajectory of a hammer in the process of manual labour, Bernstein calculated vectors of acceleration for different points of the trajectory and for different positions of the moving centers of gravity. Knowing kinetic energy in different sections of the trajectory makes it possible to figure out where the kinetic energy of the movement of the particular system in the direction of the trajectory will be the highest. Obviously, this will be the most favorable moment for the technical application of this particular manual labour movement. Besides the technical significance of such analysis of labour movements, it also presents an inspiring interest from the purely scientific point of view. Not one existing method of registering the motor reactions of organisms provides the extent of completeness and objectivity that cyclogrammographic method does. And not one of the existing methods of researching motor reactions possesses the visual representation and precision of the cyclogrammometric method. No doubt this method has a tremendous future.<sup>27</sup>

Later on, in 1933, in an essay dedicated to the development of physiology during 15 years of Soviet power, A.A. Ukhtomsky talks about:

the works of Professor N.A. Bernstein that are excellent both in design and completion ... here we will experience a new revolution in natural sciences, the consequences of which we are currently not able to realize just like the contemporaries of Leeuwenhoek and Malpighi were not able to foresee the changes that the invention of the microscope would bring to the future generations.<sup>28</sup>

Bernstein had collected a great deal of experimental material about the movements of healthy subjects and patients. He constantly questioned how the brain directs the 'mechanical machine' called the 'human body' (see Lecture 1). In calculating joint torques, he separated those that are the result of the joints' interaction from those that are brought about by the influence of the force of gravity and those active muscle forces that are put into action by the motor nerves from the central nervous system. He analysed the complexity of the mechanics of this system, where the muscles, which carry out movement, can change their mechanical properties themselves depending on the conditions of the work being executed (this is discussed

<sup>26</sup>A reprint of this Atlas was recently published (2019) <http://d-nb.info/1193129338>

<sup>27</sup>Cited from E. Loosch & V. Talis (Eds) (2014). Feigenberg I.M. *Nikolai Bernstein. From Reflex to the Model of the Future*. Berlin: LIT, p.44–45.

<sup>28</sup>Ibid., p. 47–8. Antonie van Leeuwenhoek (1632–1723) was a Dutch scientist and Marcello Malpighi (1628–1694) an Italian biologist and physician.

in Lecture 2). As he had no knowledge yet about muscle spindles—the sensory endings of the muscles were discovered by C.S. Sherrington in 1929—Bernstein presupposed their existence in the feedback circle of the motor apparatus in humans and animals.<sup>29</sup>

Later Bernstein formulated the so-called ‘model of the desired future’ based on the probability prognosis of the movement being realised. This concept then became the basis of his ‘physiology of activity’. In 1935, Bernstein’s seminal paper ‘The Problems of the Interaction of Co-ordination and Localization’ was published. In this, Bernstein discussed the ‘principle of equal simplicity’, which is illustrated by the fact that everyone, independently from the spatial metric of movement, writes his/her signature with the hand or the foot identically in any scale, or draws a circle with the hand extended in front or to the side, in spite of the fact that the muscles participating in this movement are completely different. Later on, this paper, which became the forerunner of the cybernetic approach, became Bernstein’s gift to the ‘father of cybernetics’, Norbert Wiener, when they met each other in Moscow in 1960.<sup>30</sup>

A wave of anti-Semitism travelled through the USSR at the end of the 1940s, under the banner of ‘the struggle with cosmopolitanism’. This reached the area of physical culture and sport, in which Bernstein was mostly working at that time, and he fell victim to it. The nature of this persecution, like the witch hunts of the middle ages, is shown, for example, in the protocols of the party and social meetings of collectives where Bernstein worked.<sup>31</sup> In these meetings, on instruction from the highest powers in the Soviet Union there are critiques of sports scientists connected with ‘one anti-party group of theatrical critics’!<sup>32</sup> In March 1949, the editorial in the newspaper *Sovetskii Sport* entitled ‘Let us finally unmask cosmopolites and their yes-men’ inveighed against Bernstein.<sup>33</sup> At the same time Communist Party Bureau sessions and meetings of scientific councils of the Institutes of Physical Culture in Moscow and Leningrad and the Institute of Prostheses in Moscow, with which Bernstein was then collaborating, issued a directive which threatened to Bernstein’s work situation. In 1950, there was a critique of Bernstein in the newspaper *Pravda*, the central organ of the communist press in the USSR, in the essay ‘Against the vulgarisation of the theory of physical education’.<sup>34</sup> *Soviet Sport* rushed to echo this essay in September 1950 with ‘Where are the textbooks for physical education insti-

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<sup>29</sup> Sir Charles Scott Sherrington (1857–1952) was an English neurophysiologist, histologist, bacteriologist, and a pathologist, Nobel laureate and president of the Royal Society in the early 1920s.

<sup>30</sup> Chkhaidze, L.V., Chumakov, S.V. (1972) ‘Formula Shaga’ (Formula of the Step) in *Fizkultura i Sport (Physical Culture and Sport)*. Moscow, p. 90. [In Russian].

<sup>31</sup> Personal files of N.A. Bernstein in the Archive of the Russian Academy of Medical Science, Moscow (F. 9120. V. 8/3. Unit 19).

<sup>32</sup> Personal files of D.D. Donskoi in the Central State Archive of The Institute of Physical Culture (F.9, № 1, Unit 260–292)

<sup>33</sup> *Sovetskii Sport (Soviet Sport)*, 29, 22 March (1949). p.1. [In Russian].

<sup>34</sup> Zhukov P, Kozhin A. (1950) *Pravda (Truth)*, 21 August. p.233. [In Russian].

tutes and technical schools?’<sup>35</sup> In spite of this, in 1950, the presidium of the Academy of Medical Sciences asked the scientist to start work in the Institute of Neurosurgery, where in six months, from January to June 1951, Bernstein organized a laboratory for the physiology of movement and by November was already conducting experiments. But all these efforts were in vain—in January 1952 he was transferred with his equipment to the Institute of Neurology. On 19 March 1953, the laboratory of physiology and the pathology of movement there was liquidated. Soon after, Bernstein applied to leave work on health grounds. He did so and then had no work. His wife was disabled due to asthma and they had an adolescent son, so he earned money from translations for journals of abstracts. For instance, ‘in the period from I.IV.1955 to I.V.1959 725 abstracts are completed...published in the journals *Biology* and *Mathematics*’.<sup>36</sup> Heavy daily work gave Bernstein modest means for living and the opportunity to follow the progress of physiological science abroad.

A new wave of interest in Nikolai Bernstein began among young scientists in connection with the so-called thaw which began at the end of the 1950s in the USSR and in Russian science, in connection with the interest in the new science called ‘cybernetics’ developed by Wiener, that investigates the control principles in technical and biological systems. In 1957, Bernstein was invited to make a presentation at the Department of Mechanics and Mathematics of Moscow State University in the seminar of Alexei Andreevich Lyapunov (1911–1973) and then in the Moscow physiological seminar organised in 1958 by Israel Moiseevich Gelfand (1913–2009) and Michael Lvovitch Tsetlin (1924–1966). His advanced mathematical qualification allowed Bernstein on the one hand to publish strictly applied works on the mathematics about frequency analysis in biological data that is for instance in the electroencephalogram<sup>37</sup> and, on the other, to develop the theoretical bases of modelling in biology with the mathematician I.M. Gelfand and the physicist M.L. Tsetlin. Bernstein was famous throughout Moscow and far beyond as a scientist who had retired from work, but who could be consulted by both physicians and musicians on questions of both mathematics and medicine. Every half hour new visitors with their experimental data came to his door on Bolshoi Levshinskii Lane in Moscow, where at this time he was living with his wife and son in only two rooms. Nikolai Alexandrovich valued the data highly, but he had no opportunity to run experiments and obtain this himself. The pensioner Nikolai Aleksandrovich Bernstein acted as an opponent for dissertations, wrote forewords for books, and invited young people to write joint articles for encyclopaedias.<sup>38</sup>

<sup>35</sup> Bloch L, Kosvinzev B, Nikolaev A. (1950). *Sovetskii Sport (Soviet Sport)*. 104. 2 September. [In Russian].

<sup>36</sup> Personal files of N.A. Bernstein in the Archive of the Russian Academy of Medical Science, Moscow (F. 9120. V. 8/3. Unit. 19).

<sup>37</sup> Bernstein, N.A. (1962). K analizu neperiodicheskikh kolebatel’nykh sum s peremenennymi spectrami po metody vzveshenny khreshetok (Towards an analysis of aperiodic oscillatory sum with the variable spectra using the methods of weighted lattices). *Biofizika (Biophysics)*, 7,4 p. 376–381. [In Russian].

<sup>38</sup> See, for example, Bernstein N, Kotz J (1963) ‘Tonus’. *Bolshaya Meditsinskaya Entsiklopediya (Great Medical Encyclopedia)*, 2nd edn. 32. p. 418–422. [In Russian].

In 1959, when the first cosmonauts were being trained, Bernstein advised about the possibilities for the coordination of movements of humans in zero gravity. In 1965 and 1966 Bernstein's keynote papers 'On the Roads to the Biology of Activity' and 'The Immediate Tasks of Neurophysiology in the Light of the Modern Theory in Biological Activity' and the popular article 'From the reflex to the model of the future' were published. In them, Bernstein considered the concept of 'activity' in its general biological meaning as the reason for the development and evolution of living beings. He warned about the unjustified use of mathematics in biology, stating 'do not attempt to concretise too soon the electrophysiological intracerebral picture of the phenomena by means of externally observed relations. In these last works, as before, accuracy in citation is evident, so also is the literary figurativeness of Bernstein's text and the genius's foresight in seeing the unfounded attraction with modelling of those scientists whom I.M. Gelfand calls 'modellers' and V.S. Gurfinkel calls 'keyers' (from the word 'key', having in mind those people who have one key for everything and stick it in without discrimination wherever it can be stuck!).

On the 16th of January 1966, N.A. Bernstein died from liver disease, in the house where he lived all his life on Bolshoi Levshinskii Lane, just after publishing his book *Outline of the Physiology of Movements and Physiology of Action*<sup>39</sup> but just missing seeing the publication of his first book in English, '*The Coordination and Regulation of Movements*'. Knowing, as a doctor, that liver disease is incurable, he discharged himself from the polyclinics in the last months of his life and, fearing to upset his family, left a note saying that when he passed out they should call for Volodya, a student he was close to, the future neuro-rehabilitation specialist Vladimir Naidin (1933–2010).<sup>40</sup>

Today, reading *Biomechanics for Instructors*, we see distinctly in the one part of the auditorium the young lecturer, talented, highly educated in literature, medicine, mathematics and engineering and in the other the students from whom 'The most I can ask... is knowledge of the four rules of arithmetic and basic knowledge of mechanics and technical drawing' (see the Foreword). For almost a hundred years since his book came out the science of movements has developed considerably not only due to development of technology, electronics, etc. but also to a great degree due to approaches developed by N.A. Bernstein. Equipment in a contemporary biomechanics laboratory will include a system for registering movements; a force platform to register the deviation of the centre of mass of the subject standing on it, which in Bernstein's time had to be calculated with complex methods; and electromyographic apparatus to register the activity of the muscles and sometimes, depending on scientific goals, a tomograph, electroencephalograph, etc. Bernstein only had at his disposal a system for registering movements that was groundbreaking for his time but less precise than contemporary ones. However, it must be admitted that the

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<sup>39</sup> Bernstein, NA. (1966) *Ocherki po fiziologii dvizhenii i fiziologii aktivnosti. (Outline of the Physiology of Movements and the Physiology of Activity)* Moscow, Medizina.

<sup>40</sup> Talis V.L (2019). *Doktor kotoryi lyubil parovoziki. (The Physician Who Loved Steam Engines)*. [In Russian].

high level of accuracy, which is essential, for example, for the registration of movements of the pupils of the eyes, is not necessary for movements as slow as the movements of a healthy person and even a sportsperson, so this does not diminish the value of Bernstein's book.

Thus, for example, in Lecture 9 Bernstein describes the graphic method of defining speed and acceleration of body segments—a task which contemporary PC programmes calculate analytically very quickly. Then, Bernstein, knowing the mass of the segment, graphically finds the force developed by this segment when it moves and concludes:

All the calculations that have been described might seem to you to be laborious and boring. On the other hand, how fascinatingly interesting it is when out of a lifeless cyclogram, which is like a motley net of points, suddenly one by one all the secrets of the movement which has taken place begin to appear!... You begin to feel that you have learned to read some language that was incomprehensible to you before.

Of course, what in Bernstein's time '...took about 1 month to analyse...with contemporary techniques... can be done in seconds'<sup>41</sup> but this may not always help depth of understanding of the questions being researched. The contemporary reader might not accept the material of this lecture as guidance for action but all the same will get an unique sense of how the picture of the kinematics of movement grows into the picture of forces producing this movement and can gain an impression therefore of the so-called problem of inverse dynamics.<sup>42</sup> Today in the laboratories studying living movements, the quality of force analysis of human movements depends on the elaboration of models of the human body, which, as before, are far from ideal in their approximation to living movement.

The complexity of this modelling today is still connected with the kinematic particularities of living joints, as discussed in Lecture 1. Explaining the notion of 'degrees of freedom', Bernstein says, 'Let's see now what the mobility of bones which are joined together is, in relation to one another and how to define this mobility. I am warning you that this is a rather complicated question'. It echoes a contemporary textbook on biomechanics where we read 'Degrees of freedom represent the kinematic complexity of a biomechanical model'.<sup>43</sup> What then happens when such difficult material is explained? Bernstein asks a volunteer from the audience to rotate his arm in the shoulder joint, then to flex and extend the elbow, explaining that in the first case we are dealing with two degrees of freedom and in the second, with one degree of freedom. The contemporary textbook continues, 'The degrees of freedom (dof) correspond to the number of kinematic measurements needed to completely describe the position of an object'. This is, of course, an exact definition, developed by the analytical approach, but it does not minimize the importance of the mnemonic approach of Bernstein, which he uses throughout *Biomechanics for*

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<sup>41</sup>Latash ML, Zatsiorsky VM. (2016) *Biomechanics and Motor Control*. New York: Academic Press, Elsevier.

<sup>42</sup>Latash ML (2008). *Synergy*. Oxford, Oxford University Press.

<sup>43</sup>Knudson D. (2007) *Fundamentals of Biomechanics*, 2nd Edition, New York, Springer.

*Instructors.* Bernstein's extensive description of various joints, including the particularities of the cartilage in them, appears to be a great supplement to contemporary textbooks, which are illustrated by splendid drawings, instant photographs and even references to video materials!

N.A. Bernstein is acknowledged today as the 'father' of motor control and not one textbook or book on biomechanics, kinesiology and sport physiology gets by without citing him. The hierarchical principles of movement control that he proposed are used in the construction of robots.<sup>44</sup> Music teachers learn the motor learning principles proposed by Bernstein. However, few are capable of being guided by them in teaching children music. Music teacher V.A. Guterman, who died in 1993, is a happy exception to this. The well-known Soviet physiologist L.A. Orbeli (1882–1958) said about her method of teaching music that as a result of her authorial 'method of instruction, based on the system of control of the teacher's kinetic and tactile sensations juxtaposed with the kinetic perceptions of the pupil, the latter learns by subtle analysis of these sensations, by correct evaluation and the ability to control his muscles, creating the necessary co-ordinations'. Describing her method, V.A. Guterman writes 'Genuine, great musicians...have each created their own individual technique, growing out "of their model of the desired future" (according to N.A. Bernstein), from their ideals for the sounds'.<sup>45</sup>

Guterman's method is concordant with E.V. Maximova's original method of 'abilitation' of people with autism spectrum disorder. She, a biologist by education, and well acquainted with Bernstein's theory of construction of movements, noticed in her patients 'loss of entire control levels according to Bernstein's classification'. In her book she writes, 'The children can walk, run, comb their hair, but cannot make any reaching movement (or these movements are very difficult for the child'. Having noticed this, Maximova came to the conclusion that 'the levels of construction of movements proposed by N.A. Bernstein can be regarded more widely, as levels of psychic reaction'. Maximova's method is based on the assumption that 'in many psychic pathologies disruption of perception is primary and disruption of communication, disruption of emotional reaction, disruption of behaviour, are secondary'.<sup>46</sup> Making use of methods of bodily therapy, Maximova tries to build up step-by-step the 'lost' control levels according to Bernstein's classification beginning with 'tonic', the 'more ancient' and finishing with the most complex, such as the highest cortical level of speech and writing, the most difficult for the patients in this group.

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<sup>44</sup>Poramate Manoonpong, Geng, T, Kulvicius, T, Porr, B, & Wörgötter, F (2007). 'Adaptive, Fast Walking in a Bipedal Robot under Neuronal Control and Learning'. *PLOS Computational Biology*. Vol. 3 p. 1–16.

<sup>45</sup>Guterman V.A. (1994). *Vozvrashcheniye k Tvorcheskoi Zhizni. Professional'niye zabolevaniya ruk. (Return to the creative life. Professional diseases of the hands)*. Ekaterinburg Gumanitarnoe-ecologickii Litsei. [In Russian].

<sup>46</sup>Maximova E.V. (2008) *Urovni obscheniya. Prichiny vozniknoveniya rannego detskogo autisma i ego korrektsia na osnove teorii N.A. Bernsheina (Levels of communication. Reasons for the emergence of autism spectrum disorder in early childhood)*. Dialogmifi: Moscow. [In Russian].

It must be noted that today, although the levels structure of movement control is apparent, concrete morphological substrates of localisation of one or another level remain undefined as they were in Bernstein's time, in spite of the progress of brain research. But all the same, why do not only specialists in motor control but also educationalists, trainers, musicians, physiotherapists and mathematicians find in Bernstein through his works a teacher and ally? The answer is very simple: through his genius, the combination of his deep insight in several branches of science led to the birth of the new science of movement control, of which he is considered the father. The outstanding mathematician of our time I.M. Gelfand said at the funeral of physiologist N.A. Bernstein that we are burying 'an outstanding mathematician'. Despite this, we can say that Bernstein is still not fully evaluated and understood by his compatriots (the essay about Bernstein in the German Wikipedia is 2.5 times longer than the Russian one).

Bernstein has left us two popular books, one of which was translated 20 years ago and the second lies before you now! Like Bernstein's students, listening to Bernstein in the cold Moscow of 1925, let us arm ourselves 'with the four rules of arithmetic and basic knowledge of mechanics and technical drawing' and go forward keeping in mind the logic of the outstanding scientist with a tragic fate—Nikolai Aleksandrovich Bernstein!

Vera L. Talis

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