C3

WE ARE OUR ACTIONS

Would N.A. Bernstein Research BCI?

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Finally, the translation: Years ago, and more than once, Mark Latash, who did a lot to present the work of N.A. Bernstein to the scientific community, deplored the absence of a translation of his most important book, *On the Construction of Movements*, published in Moscow in 1947 (1947a). Before him, David Adams – who in the 1970s went to study in Moscow (and worked with the Georgian physiologist, Tengiz Oniani) – translated a first chapter (Adams 1978). Micha Mirsky, who knew Bernstein quite well (he wrote about his conversation with "Uncle Kolya," as he called him) and interacted with him (his father's office was next to Bernstein's) going back to the fall of 1944, also tried his hand at translating Bernstein's famous book. The famous mathematician Israel Moyseyovich Gel'fand (Kyoto Prize, MacArthur Fellowship), usually cited as Gelfand, was supportive of Mirsky's attempt. In his endorsement of Mirsky's effort (intended to help secure funding), he correctly pointed out that the book gave "rise to a new way of understanding how complex systems work" (Gelfand 2009). I shall borrow from Gelfand the moniker NAB, "standing for Nikolay Aleksandrovich Bernstein (1896–1966)" fully aware that given Bernstein's inclination to a formalism meant to express respect, he might have objected to the unintentional slight.

Maybe others have also tried to translate the book. (At this time, a translation into the French is in the works.) This is significant for understanding the role played by those who dedicate themselves to the task of facilitating access to contributions written in languages other than the dominant English. Within the culture of the Soviet Union, which for a long time locked itself in a condition of autarchy contrary to the free exchange of ideas, other publications had a similar destiny. For anyone aware of the major questions that science addresses, it becomes clear that NAB's influence in the Soviet Union was maybe not very deep, but of lasting effect. During a time when to even acknowledge him was considered risky, his reputation deservedly increased. Bernstein's activity gained respect abroad also, in particular in Germany, and eventually in the USA, after several eminent Soviet scholars made America (the USA and Canada) their home of choice – quite a change from their home of birth.

Recognition is good, but influence, in the sense of affecting the progress of science, is better. On this account, NAB's impact is rather under-, not over-, whelming. In a very thorough presentation in the *Journal of Motor Behavior*, Bongaardt and Meijer (2000) placed NAB's "Theory of Movement Behavior" in a historic perspective They took note of the fact that from ca. 140 original contributions (Feigenberg 1988), only 24 had been translated (into German and English).

The situation has changed since. While his work is constantly referenced, there were rather few examples of being carried forward. Almost 20 years later, in *Human Movement Science*, Profeta and Turvey (2018) acknowledged the progress made in "the science of the control and coordination of movement," indirectly confirming that it is not really triggered by NAB's understanding of movement. Asking whether "Bernstein's levels" could accommodate "Complementary Conceptions of Synergy" (Bruton and Dwyer 2018), take note of NAB's "Elegant solution to the problem of coordinated movement and the development of skilled action (p. 2766). He has followers, scientists who deem his "construction of movement" as foundational; but in the new context of science, his most significant ideas are not found to be inspiring, or remain ignored. I had the opportunity to review an article in which Bernstein's fundamental position vis-à-vis Pavlov is fully ignored (Pool et al. 2019), despite the fact that he addressed exactly the aspects discussed in that more than deficient publication. The "gatekeepers" at the *Nature Human Behavior* journal would not agree that the omission of NAB's fundamental work undermined the article in question. Actually – and this is extremely important – the Bernstein "revolution" starts with his exceptional analysis of the shortcomings of Pavlov's reflex theory. While acknowledging Bernstein, the neuroscience of motoric expression either avoids his fundamental ideas or seeks details that justify more fashionable, i.e., computational, models. Is the explanation to be found in the language barrier? This translation will provide an answer. Or should we try to identify what else explains the very timid integration in current research of his breakthrough ideas? This is the subject I shall try to address in this study.

Marginalia

NAB was an autodidact (as were, by the way, none other than Galileo Galilei, for example, George Boole, and Charles Darwin), trained in a medical school, but not in physiology in particular. You could succeed without a diploma in the early stages of the Soviet Union because the revolution promoted opportunity and downplayed the role of Academia, where the regime suspected less than full support. Home-schooled Konstantin Tsiolkovsky – a pioneer of rocket science – is yet another example mentioned by those who view talent and dedication more important than a diploma.

From various sources of testimonies (by friend and foe), it is apparent that NAB was a difficult character. He expected to always be right, while never failing to be extremely polite. A Soviet intellectual characterized as a "loyal dissident" (according to Meijer and Bruijn 2007), dedicated to the idealistic image of a new society – but not unaware of its limitations. It was easier for him, as it was for other intellectuals, writers, and artists, to be a devoted Soviet citizen, dedicated to the ideals of socialism, than to question any of its shortcomings. Out of conviction, he served as a physician in the Red Army. To acknowledge prejudice, opportunism, dogmatism, and the authoritarian nature of an ideology of intransigence and intolerance that eventually affected his life was not a feature of his profile. The winner of a Stalin Prize (associated with the name of a dictator, yet on a par with the Nobel Prize, associated, as we know, with the name of the inventor of dynamite), for the book we comment upon in these lines, was unceremoniously kicked out of his work once he was denounced as an "uprooted bourgeois." Ideals died the day when some of his comrades (some friends included) played their well-rehearsed role of declaring him and his ideas as dangerous. The way Bernstein was treated in the context of a campaign of anti-Semitism that affected many (some Jews lost their lives) was interpreted in a manner that NAB would have rejected. His parents converted under Tsarist Russia in order to advance their careers. An atheist himself, he never felt any affection for an identity that implied religion. To spell it out clearly: NAB was rejected not as the person he never was, but rather as an author of ideas that the ideology of the day considered

FIGURE C3.1 Gheorghe Marinescu (1863–1938) Early attempts at describing the motoric system using cinema recordings.
(Source: Courtesy of the Romanian Film Archive and provided by film historian Bujor Ripeanu).

inadmissible. This fact deserves attention because, at a later time, in a society that does not punish nonconformity to dogma, ideas as revolutionary as Bernstein's were killed by simply being ignored. I refer here to the scientific destiny of Robert Rosen, and of Walter Elsasser. We shall return to this in our discussion of NAB's most controversial views.

Andres Kurismaa (at the time a graduate student at the University of Osnabrück's Institute for Cognitive Science), who connected the dots between anticipatory systems (as I presented the subject in 2011 at the University) and NAB's model of the future underlying motoric expression, insisted that I pay attention to Bernstein's writings. I knew about his work, but had not begun to study his various contributions in detail. Somewhere in my past was the connection to another scientist who studied movement – Gheorghe Marinescu (1863–1938), known in the French-speaking world as Marinesco. He was an early user of film recording for evaluating conditions such as hemiplegia, paraplegy, and locomotion ataxia (Figure C3.1). Incidentally, he was also fascinated by the electric aspects of the physiology of movement (transmitting electric waves associated with motoric expression over telephone lines).

But NAB, as I soon learned from reading some of his books, was on a path that transcended the focus on neurology that characterized Marinesco's distinguished work. Questions regarding the role of the future articulated by NAB also tempted Leon Abgarovich Orbeli, Pyotr Kuzmich Anokhin, Konstantin Andreyvich Ukhtomsky, Ivan Solomonovich Beritashvili, and a few others who noticed how purpose affects action. And all of this in the 1930s and 1940s, in a country where the official line prohibited such views.

Discovering the Pioneers

In the state of mind of a researcher who on his own discovered anticipatory expression related to creativity (Nadin 1972, 1990), I was encouraged to find out that, almost at the same time, Robert Rosen worked on defining anticipation. Ignorance could be bliss: as I understood, after the abovementioned discussion at the University of Osnabrück, NAB came into the picture as the "giant" on whose shoulders I was not standing, because I was not aware of his broader perspective.

Neither were his distinguished colleagues (mentioned above) the source of inspiration for my own questions. Nevertheless, I could ignore his views only if I were willing to pay the price that those dedicated to research ultimately pay, willy-nilly, for their ignorance when the state of bliss is smashed. At this juncture, only one thought: although Bernstein's work eventually made it across the borders between the Soviet Union and the rest of the world, his work, as well as that of his colleagues interested in anticipation, remained, as I mentioned in the introductory lines, of limited impact. The 2014 Nobel Prize in Physiology and Medicine ignored the work of Beritashvili (Nadin 2014).

The absence of an English translation of Bernstein's most important work on motion – published in 1947 – partially explains the situation. Reading the various books and articles on motoric expression published after NAB's foundational contribution, the readers will realize that what is missing is not the formal acknowledgment of his role, but rather the opportunity to benefit from a new angle, a new epistemological horizon. Science advances through discovery and dialog. NAB submitted his original views – discovery, based on a long-term commitment to experimental work and testing of hypotheses – but no dialog ensued. It was a conceptual revolution that engaged few others – his followers, mainly. In the Soviet Union, until his late rehabilitation, his ideas were not acceptable even as a subject of criticism. The book on Pavlov's view remained unpublished, not because NAB avoided offending his memory (the nice moralizing tale that since Pavlov could not counter, Bernstein refrained from attacking his theory). It was not published because it did not receive the "seal of approval." The Germans speak of *Totschweigen*: "death through silence" or "wall of silence," i.e., not even talking about something destined to be ignored. In the West, some scientists heard about the manuscript, but the Nobel laureate Pavlov was already the scientist in whose footprints so many stepped. The prolonged absence of translations has undermined communication: NAB's work was acknowledged but rarely analyzed in depth. Some exceptions: Pickenhain and Schnabel (1975), Sporns and Edelman (1993), Feldman and Meijer (1999), Bongaardt and Meijer (2000) and very often Latash (e.g., Latash and Latash 1994).

Returning to context: His book On *the Construction of Movements* (1947a, in Russian) and a subsequent book, *On Dexterity and Its Development* (1947b/1991) – which Iosif Moiseevich Feigenberg, also known as Josef, a scientist I shall return to, published – allowed me not only the realization of NAB's pioneering work, but also of many aspects I had failed to realize in the absence of healthy scientific dialog (Figure C3.2). Many other scientists interested in NAB's work would (or should) probably say the same. Cross-pollination is as vital in our interaction as it is in agriculture.

No time for regrets. We never live in the past of errors and missed opportunities, but rather in a *sui generis* present of new opportunities. NAB's book, in its English translation by Mark Latash – tirelessly ascertaining the role NAB played in the establishment of a solid scientific foundation for a science of motion – should help us all (not only historians of science) to catch up with his original ideas. The fact that a scientist who himself has contributed much to the field made it his priority to translate the book deserves to be highlighted. If Bernstein sometimes encountered less than favorable circumstances, he is now the beneficiary of probably the most competent translation he could have hoped for.

"Activity Constructs a Motor Skill"

In his introductory remarks, Bernstein wrote candidly about the rather incomplete factual material, the hypothetical nature of some of his interpretations, and even about some subjectivity that

FIGURE C3.2 NAB's books *О построении движений*. М.: Медгиз, 1947 (*On the construction of movement*, 1947 edition), and *О ловкости и её развитии*. М.: Физкультура и спорт, 1991. *Публикация подготовлена профессором И. М. Фейгенбергом (On Dexterity and Its Development,* Professor I.M. Feigenberg, Ed., 1991) found their way onto my desk and into my library.

infiltrated conclusions. It is in connection to his own words that some comparative thoughts are justified, and examples juxtaposed. It struck me that in my research of anticipatory expression (since 1995 and ongoing), at times I pursued, unknowingly, means and methods that belong to the "family" of experimental work that NAB carried out. The fact that I had the advantage of eventually living in a time and a place of more scientific opportunities – though not necessarily of less dogmatism – is not my merit.

These images, of documentary interest, conjure little discussion – you cannot really compare the technology of the 1930s to that of the twenty-first century. They juxtapose NAB's experiments (late 1930s) and the data collection on the AnticipationScope (ca. 2007–2008). In some ways, they testify more to the similarity of perspective: how to describe human action as it unfolds naturally, i.e., avoiding the danger of disturbing in the process of measuring. His focus on activity (the title of this section is a quote from the book) and ours on action are very close. As we shall see, there is no agreement on what experimental data afford, and no agreement on how to interpret what we observed. NAB conceived of the kymocyclographic camera for making visible the pattern of the kinds of movement he focused on. I conceived of the AnticipationScope, combining the time-indexed digital recording of movement with physiological sensors capturing data significant to the movement (Figure C3.3). He analyzed goal-oriented motoric expression: athletic performance, work, piano playing. We at the Institute for Research in Anticipatory Systems analyzed similar subjects, but with additional means. Not limiting ourselves to the motoric system, but considering

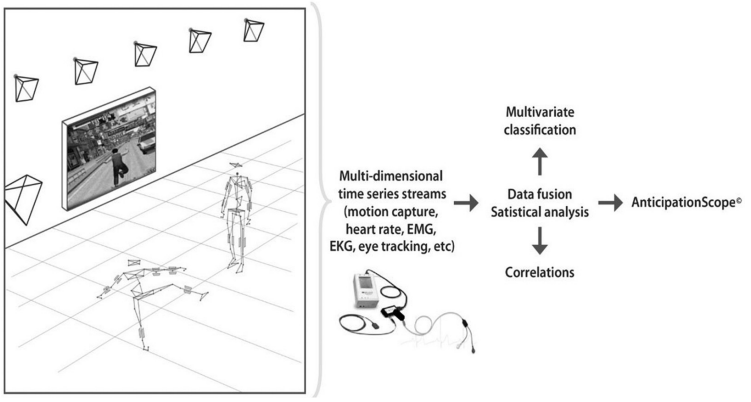
also the cardiovascular profile, the neural profile, and the hormonal profile, we came close to a holistic view. The result is the Anticipatory Profile (Nadin 2012), not the description of particular movements.

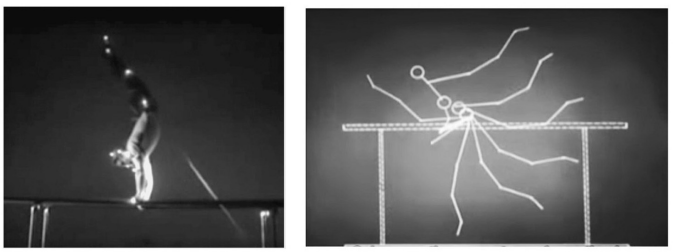
NAB's major realization, in short, is the variability principle: "Repetition without repetition," behind which the relation between a large number of degrees of freedom and the possibility of control processes looms large. Incidentally, this idea was documented in my contribution to the volume *Anticipation – Learning from the Past. Early Soviet/Russian Contributions to a Science of Anticipation* (Nadin 2015). This volume is the result of the discovery that before Nadin (1972, 1987) and Rosen (1985), there was an entire school, in what used to be the Soviet Union, that advanced hypotheses on anticipatory expression. Well, before them were Leonardo (to whom we shall return) and a number of others who noticed anticipation expression (Nadin 2010). NAB was probably the most significant, given his dedication to nothing less than how life is expressed: in motion. He did not specifically seek to generalize his findings (which integrate evolutionary aspects as well) to nature. In regard to the human being, he definitely proved that the mechanistic view, as he described the dominant reflex theory of the time, was not the answer to understanding motion.

Activity Means Purposeful Action

Recent spectacular accomplishments associated with an understanding of the human being contrary to what Bernstein ascertained in his book have cast a shadow on the celebration of its translation. Does NAB's path in exploring one of the most difficult aspects of how life unfolds lead into the nowhere of inconsequential speculation? Or do we pursue directions in defiance of what the "compass" of informed experiments and generalization indicate? The question of whether NAB would pursue brain-computer interface (BCI), featured in the title of this study, is only illustrative of the concern with the condition of science: the theology of the machine model vs. the understanding of the unfolding of life as an expression of anticipatory processes.

If Bernstein's book, in the author's own words, is more a "program for studies to be conducted in the immediate future than a dogmatic report …" let's imagine a NAB asked by his employer (a Soviet Union Institute) to dedicate his work to how the brain guides limb control. This is hypothetical. In reality, he was asked to work in prosthetics (a subject to be revisited soon). In other words: to address, in this hypothetical situation, the hot issues of brain–computer interface that dominate the agenda of motoric expression research. Let's not forget: The Soviet Union tried to compete with the West (i.e., capitalist science) – yet another aspect to be soon recalled. This "what-if" scenario needs to be properly framed. As a Soviet scientist recognized for his contributions, NAB – instigated by an idealistic Alexei Gastev, who organized the Biomechanics Laboratory at the Central Institute of Labor (CIL) – studied motoric aspects of work: hitting a chisel with a hammer, the performance of gymnasts, and piano playing as part of a broader interest in all aspects of such activities. That scientists are often opportunistic is an observation that is neither new nor equivalent to a value judgment on their character. As much as we wish to idealize science – in principle it does not carry a party membership card – we all realize that society, in some form or another, provides the means for facilitating research. NAB studied motoric control associated with labor because the Soviet society wanted to extract more efficiency from its laborers, the living machines of the time. He himself mentions the Stakhanov model – a competitive scheme (subject to many jokes) meant to reward the most productive. The Soviet gymnasts were trained to be better than those in capitalist societies, and so were the pianists. Ideology penetrated the scientific agenda. It goes to NAB's credit that he internalized the motivation, but never compromised the integrity of the scientific endeavor to which he dedicated his life. During my own experience





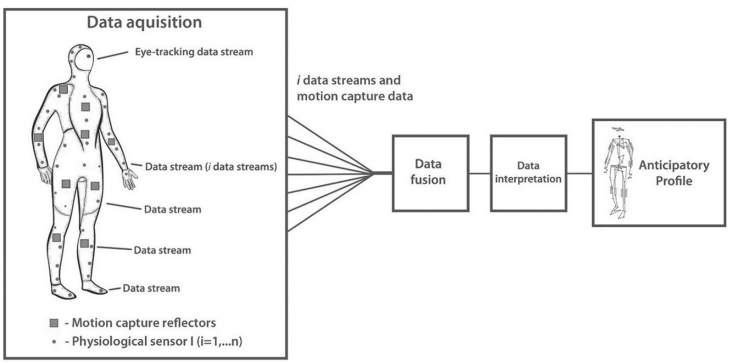


FIGURE C3.3 The kymocyclographic method and the AnticipationScope.
Unaware of NAB's experiments, we tried to describe the anticipatory expression of piano playing, and of gymnastics, which were also of interest to Bernstein. His outcome: visual representations. The outcome of the AnticipationScope: a combination of data defining the Anticipatory Profile and dynamic representations of purposeful actions.

under a communist regime, I learned from many of my distinguished colleagues that this was not easy. Science could land you in jail. Gastev, the enthusiastic Bolshevik, who instigated NAB to research labor, was killed by his intransigent comrades.

The book we discuss synthesized research carried out over 25 years. It appeared after the end of the brutal World War II. It is dedicated "to the memory that burns bright forever of comrades who gave their lives fighting for the Soviet Motherland." These words deserve our attention. Deep down, the superb researcher was respectful of the lives of his comrades. Eventually the idealistic NAB himself, with convictions he never gave up, suffered. His scientific arguments – in particular those that criticized Pavlov's view – were deemed contrary to the official line. Consequently, after having received the Stalin Prize (also known as the State Prize) for this book, he was ostracized from the scientific community after a meeting called by those who wanted to clean Soviet science of any foreign influence. He was eventually rehabilitated. Still, if the Soviet Union had said, "Nikolai Alexandrovich, we need your help for our war heroes …" (millions of men lost limbs or were paralyzed). Or: "Look, we need a powerful military, brain control of artificial limbs could help us defend the Motherland," NAB probably would have obliged. After all, among the many places where he worked – Institute for experimental psychology (1925–1927), Institute for the Protection of Labor (1927–1933), Institute for Music Studies (1926–1940), Central Institute for Handicapped work (1932–1941); the Institute for Experimental Medicine (AIER) was also the Institute for Prosthetic Appliances (from which he was fired in March 1949). However, and with this hypothesis we end the "what-if" scenario, a Bernstein approach would have been grounded on his fundamental view of purpose-driven motoric control or, better yet, of goal-driven action.

Let us recall that NAB's work – I make reference to many of his articles that eventually fused into the book published in English translation – the brain does not, and as a matter of fact cannot, "prescribe peripheral mechanics (or muscle activation)," as Mark Latash noticed (private communication of September 25, 2019).

At the Institute for Prosthetic Appliances, NAB contributed original ideas to designing and constructing devices (lower limb, arm) based on the "construction of movement," his foundational work (Figure C3.4).

Without providing here an exhaustive overview of his original contributions, let us mention the article "Normalization of Walking on Prosthesis with an External Power Supply" (Shishmarev et al. 1974), and an even more specific application of NAB's ideas (Farber and Jacobson 1995), "The theoretical aspects of our development are based on the work of Bernstein" – with specific reference to his articles "On the Construction of Movements" (1947, in Russian), and "Essays on the Physiology of Movements and Physiology of Activity" (1966, in Russian). Of course, at that time, BCI had not entered the picture; but there is the documentary evidence that the passionate physiologist of movement did not shy away from technical innovations.

Fundamental Knowledge as Scaffolding for Applications

The purpose of insisting on such specific aspects is self-explanatory: there is a mechanistic-reductionist path, which he rejected, and there is a Bernsteinian path to addressing impairments, based on a foundational view of motoric expression as part of purposeful actions through which the human being experiences the world. The question of whether NAB would have gotten on the BCI bandwagon – as many reputed researchers (e.g., Georgopoulos, Schwartz, Hochberg, among others) have, can be answered in the negative. To implant microelectrodes in order to activate a prosthetic arm of impressive capabilities is a spectacular feat. But it was in

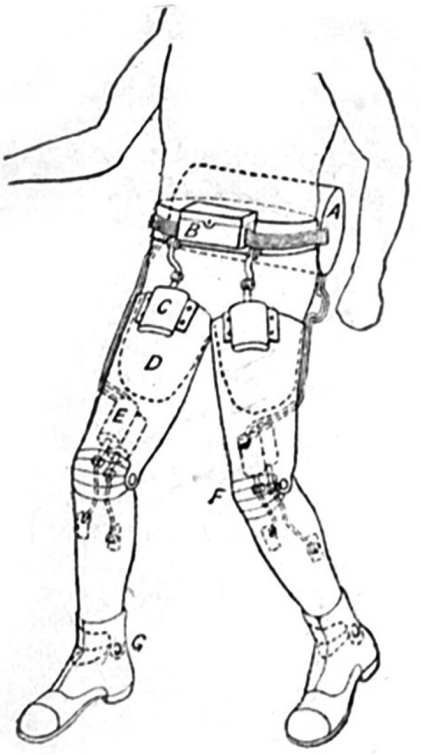


FIGURE C3.4 Prosthetics with an external power supply for activating small electric engines, inspired by NAB's views on the motoric.
(Source: from a private communication with Vera Talis).

contradistinction to NAB's view of the integrated motoric system and its relation to the brain or to the mind – or to both. It is a bit disappointing to find out that NAB's fundamental contributions were ignored by those who got involved, and as they still are, in the many attempts to emulate human motion that we experience in the age of AI and robotics.

But let us proceed step-by-step: the machine model of the living – the human being, in particular – going back to Descartes (but not only, see de la Mettrie, *L'homme machine* 1748) – implied the brain control of motoric expression (although Descartes, agnostic of the brain, focused on the pineal gland). This model was eventually adopted once the computational paradigm took over. Indeed, in its current embodiment, the machine model is understood as "We are computers" (as Popper 1966, saw coming) or, more recently, "deep learning" neural networks. Brain control of motoric components (limbs, in particular) translated as the path of control mechanisms for artificial replacements. The prostheses of the Industrial Age, based on the mechanics of the machines in factories, were successfully replaced by artificial "spare parts" (arms, legs, knees, etc.). Bernstein, who was learning about the brain by examining motoric expression, deplored the impossibility of examining the brain directly. With the emergence of neuroscience, monkeys became the substitute, and in 1970, brain signals recorded in the motor cortex of monkeys made available data on some forms of controlling motoric expression (Humphrey et al. 1970). Shortly afterwards (Georgopoulos et al. 1983), identified correlations to movement, and even signals before the onset of action – a real Bernstein moment, but never acknowledged as such. Wasn't this, one wonders,

what Bernstein described as "the model of the required future"? Unaware of his pioneering work, exceptional scientists have been reinventing the wheel. But not really, since they failed to understand the depth of motoric expression, its epistemological meaning. Not even Benjamin Libet (1985), whose work inspired the early stages of my own research on anticipatory expression, was aware of NAB. He showed what "readiness potential" is; but while having access to real brains via EEG data, Libet did not understand motoric expression as the conduit to the brain. The fact that mind processes took place in advance of actions (the mind "guessing") suggested to him some selection procedures in the brain.

Of course, the case can be made that we are comparing apples and oranges. Implanted recording microelectrodes are based on a science quite different from that underlying the understanding of life from the perspective of goal-oriented actions. Neither Libet (himself only marginally acknowledged by the superb technologists of brain–computer interface), nor Georgopoulos, nor Schwartz (2004), nor Jiping He and colleagues (2005) ever considered the type of questions that NAB formulated in researching the motoric system and its relation to the brain and the nervous system. The reciprocal statement is also worth considering: Did NAB ever consider the challenges implicit in conceiving prosthetic devices interfaced to the brain or the nervous system? The Institute for Prosthetic Appliances turned out to be one of those places where competition with capitalist science led to developments worth remembering, even if the technology deployed at that time was quite rudimentary.

As an anecdotal parenthesis to our focus on Bernstein's theoretic contributions and their relevance to practical aspects, it is worth recalling that almost at the same time NAB, correspondent member of the Academy of Medicine, got his Stalin Prize, a one-armed, uneducated blue-collar worker received the same distinction. He conceived and manufactured (literally) a prosthetic arm, in the context in which millions of disabled veterans of the World War II desperately sought help in order to get on with their lives. The Kononov arm (Ruka Kononova) was featured in contrast to the American "Wonder Arm" of that time (indeed functional, but pretty ugly). In the Soviet Union, the Kononov prosthesis was even compared to the Tupolev bomber (an impressive aviation accomplishment). The rudimentary prosthetic arm was yet another "Potemkin Village" promise: i.e., the illusion that diverts attention from the real deception. Frances Bernstein, 2015, wrote about this in "Prosthetic Manhood in the Soviet Union at the End of World War II." NAB was working on a prosthesis that reflected his understanding not only of how arms functioned, but also of how the motoric is an *integrated* system within which control processes appropriate to the degrees of freedom (of the arm in this case) afford the appropriate performance. The question of whether Bernstein would have done BCI, if he had lived in the computer age as his late colleagues did, in order to make use of a technologically advanced prosthesis is relevant to the Kononov moment in the sense that fundamental knowledge should provide the scaffolding for applications even during the time when technology bursts ahead of science.

Within a short time at the Prosthetic Institute, NAB came up with concrete answers to practical questions pertaining to conceiving, designing, and manufacturing prosthetics (as we have seen, Figure C3.4). The interface was not to computers – the digital age was far off – but to the technology available at that time. Theoretic discoveries, tested in the laboratory using "original" recording methods – mirror recordings of movements, cyclographic techniques to track movements followed by the use of his original cyclocamera – constituted not only a perspective – the prosthesis must reflect the nature of human activity, its purposefulness – but also the foundation. At present (and this is true also for the last 50 years) such a foundation is missing most of the time, although the results of this "seeking in the dark" cannot be ignored. On a website dedicated to movement and its relevance to sports (Myszka 2018), NAB's ideas are applied to football: "how

the masterful movers' ability would show itself in the skillful organization of movement." The entry is titled "Respecting the movement problem." One wishes that the stars of BCI technology had realized the same. Although ignoring NAB's fundamental contributions, good reviews of how BCI support prosthetic control were made by Taylor (2002), Schwartz (2004, 2007), and Hochberg et al. (2006), proving the point I am making: there is a lot of show-and-tell in spectacular neuroprosthetic control (a journal is even dedicated to the subject), but little on the underlying science of such control mechanisms.

The "One Problem" Scientist

NBA would have had a tough time getting funded by DARPA, but he would have continued on his path. I am not the first to notice that Luria (1987) was right in his assessment: Bernstein "was a rare case of a scientist who practically devoted his entire life to one problem: The physiological mechanisms of human movements and motor actions" (p. 85). I wish that Luria had chosen the word "processes," instead of "mechanisms."

The fact that the brain is an effective mapping processor became known once the neuronal theory of the brain was advanced. But the path of using the brain (in particular the motor and parietal cortices) for the purpose of motoric control in disregard of its characteristics is rather dangerous. Unrelated signals can be used in order to accomplish tasks that in our days are described as typical of the "transhumanist" age, i.e., transcending biology. For example: no longer associating data to motoric activity as an expression of purposeful life, but using the biological substratum (the brain, in particular) for controlling the flight of not just one drone (or whatever), but of several. Implanted arrays in both hemispheres of the brain could indeed serve as conduits for synchronous operations that will result in enhanced soldiers and multi-drones, as well as in behaviors that negate the human nature of the species. NAB probably would have shared in the enthusiasm for scientific and technological progress, but not to the extent of joining in the "show of bells and whistles" to which, in our days, even the most brilliant among us too often succumb.

Kononov's arm prosthesis worked fine, within the constraints of a mechanical contraption useful in one case and only one situation: when it was custom-designed and individually produced. That over time it failed, as the manufactured arm aged and the individual using it underwent biological changes, goes almost without additional explanation. Evidently, BCI-driven technology can also be custom-made, and even endowed with adaptive features: it can "learn." And it is, not unlike Kononov's artifact, successful – to the extent that it inspired a great amount of media reporting, including a relatively large article in the *New Yorker* (Khatchadourian 2018). But the experiment, at a scale of science and technology deployment that no one else can even dream about (never mind the huge cost), had to come to an end. There were too many parameters to even consider: picture a person having an array of sensors (the extremely impressive Utah arrays) implanted in the brain and the possible interaction between the Utah arrays and the brain. As one reporter put it, it was "a Frankenstein" image: two cylinders were protruding from the subject's head. Never mind the "hard-wired" solution defying the awareness of the adaptive nature of the human being, in particular that of the motoric system. "Give me a human with a hundred electrodes in his head," as the leading scientist of the Revolutionizing Prosthetics Project said, "and I can do all sorts of things," (Khatchadourian 2018, p. 63). Interfacing to the Applied Physics Lab (APL) arm, yet another amazing technological accomplishment (receiving millions of dollars in subventions), was one of them. The spinocerebellar degeneration of the subject willing heroically (or desperately) to link her brain to the robotic arm was of no concern. For the sake of preserving the integrity of

this report, it is only fair to acknowledge that one major player, Schwartz et al., (2006) was aware of some of NAB's work (but not of *The Construction of Movement*). He even understood variability and highlighted NAB's contribution to rejecting the localizationist dogma:

> muscles must act to generate force that moves the body in context of the environment. The environment is constantly changing, so that in order to make the same movement, different muscle activation patterns would be needed.

Further down, the explanation:

> we arrive at the conclusion that the hypothesis of cellular localization of muscles necessarily leads to a denial of cellular localization of conditioned reflexes.

Unfortunately, this correct understanding of NAB's position is abandoned when the author delves into neuroprosthetic engineering. Moreover, the experiments (in which not only Schwartz, but also many others were involved) on monkeys (*Macaca mulatta*) entirely ignore NAB's very detailed description of the levels of construction of movement, corresponding to a deep understanding of how motoric expression testifies to evolution: "No other physiological function has shown such an intense and, moreover, accelerating phylogenetic progression" (Bernstein 1947). As readers will notice, NAB was quick to correct himself: "The evolutionary progression of the central processing systems." It is worth (and justified) contrasting the consequences of the reductionist view (expressed in BCI-driven prosthetics technology) to the promises of an integrating foundational perspective, such as the one NAB advanced.

This understanding was expressed before computational reductionism became dominant: more precisely at the NCMRR [National Center for Medical Rehabilitation Research] Conference on Prosthetic-Orthotic Research for the 21st Century (Bethesda, Maryland, July 23–25, 1992). Dr. Dudley Childress, recognized for contributions in rehabilitation engineering, spelled out a view of what motoric expression is that came close to NAB's fundamental perspective:

> I view motion analysis data as being similar to the observational data of the planets some 500 years ago. Much data was collected by many observers with varying degrees of accuracy, and it was difficult to put the measurements together in a coherent and unified fashion. Kepler, through mathematical description, and Newton, with the theory of gravity, were ultimately able to bring the information together in an understandable and relatively simple way. I think the same thing will be done with human locomotion.

He finished the editorial with a cautious assessment: "Other paradigms may already exist for the field; for example, I wouldn't be surprised if some of the concepts of Nikolai Bernstein (1967) might be of this nature." They are – in particular his views on anticipation.

Bernstein and Anticipation

There are good reasons, as we shall see, for considering *On the Construction of Movements* in the category of contributions made by Kepler, Newton, Einstein, and the quantum mechanics physicists. The focus on NAB's fundamental perspective invites us to consider the broader

implications of his long-term dedication to understanding movement as an expression of life. At this juncture, I would mention Latash's book *Fundamentals of Motor Control* (2012), in which he describes motor control as "an area of science exploring natural laws." While the focus is on motoric expression, Latash builds upon NAB's views ("father of contemporary motor control"), delivering not only a solid historic review, but also a guide for future work in understanding motor control. After describing NAB's multi-level system for the constructions o movement, Latash makes it explicit that "nearly all human movements are built on several levels." Bergson (1911) quite suggestively framed the larger problem in almost Bernstein terms: If I raise my arm, the position which it successively occupies in space explain its movement, or does the movement explain the positions which the arm successively occupies in space? Let us take note that, without explicitly acknowledging each other, NAB and Bergson also shared in their views on the nature of the living.

The meaning of what NAB contributed (I make reference to Veresov 2006) is evinced in two lines of thought that stand out: "from reactiveness to activeness" and "from mechanism to organism." We should add: from action to purposeful action. Behind this formulation one finds "Contemporary Issues on the Physiology of Neural Processes" (finished in 1936, published in 2003) and *The Physiology of Human Movement and Activity* (1987). Luria's above-mentioned description of NAB's research agenda, puts the entire endeavor into focus. While it is true that the motoric is, as NAB stated, a window to the brain, the aim of his work was not to form a theory of the brain, but rather to suggest a broad view of what life is and how it is expressed in action (human action, in particular). Goethe's thought – *We know ourselves through action* – goes hand-in-hand with *We know the world through our actions*. Indeed, in writings that reflect the questions NAB entertained after publishing his two foundational texts (1965/1988, 1969), he attempted a difficult synthesis. The living, at all levels, is identified through activity: it "pursues goals." Activity itself unfolds against the background of the variation and selection processes through which evolution is expressed. Every living entity is "making itself" (an idea that many years later necessarily emerged in my own views, Nadin 1991), in what he described as the "anti-entropic structuring of the self." Reporting on this, Bongaardt and Meijer (2000, p. 666) summarize NAB's position: "activity is not restricted to movement behavior, but can be found at all levels of life, from molecular complexes to brains." NAB was even more precise: activity is evinced "in all possible manifestations of vital activity both in onto- and morphogenesis, and in all forms of interaction of the living organism with its surroundings" (Bernstein 1969, p. 120).

The slime mold (without a brain, of course), and also plants and all kinds of living entities (from the mono-cell to the human being) display behaviors – which means they are active – informed by goals that lie in the future. The unfolding of life, in all its forms known so far (archaea, fungi, protists, bacteria, plants, animals), is by necessity *anticipatory*.

To be alive is to act in order to maintain life. Hence, the possible future – a new entity – becomes part of the complex process through which the living constitutes itself. This process integrates reactive components (interaction of matter) and anticipatory actions – from defensive behavior patterns to creative endeavors. When, based on its still rudimentarily acquired data, Bernstein advanced the variability principle – no motion is ever identical to a previous motoric expression – he was probably not aware of the very broad implications of his observations. In my opinion, repetition without repetition actually qualifies as a universal law of the living. Let us shortly explain why I came to this conclusion.

Aristotle is credited with a formula (recalled by Elsasser 1958): No two blades of grass are the same. Likewise, Leibniz referred to leaves on a tree ("never the same"). Today we know more: there are no two identical cells in an organism, not to mention neurons, or identically

folded proteins (Nadin 2018a). The mechanical view, exemplified by the self-duplicating machines that von Neumann (inspired by the Turing machine) advanced, originated in the theology of the machine: Humans made machines of all kinds in order to become more effective. To ascertain that humans are machines – for example, life as an internal combustion engine, an idea shared by many reputable scientists in the last century – is to hypostatize: ascribe real existence to our own constructs. The making of an idol (a piece of wood, after all, as good for burning as for veneration) leads to theology. Evidently, the theology of the machine ascertains what logic defines as identity: perfect repetition. The reason is an expression of the expectation that machines embody physical laws that actually capture the identical in the reality. The law predicates monotonic performance: each time an action is triggered, the machine delivers the same. A tourist from Sirius seeing an athlete might have seen "an impressive machine, unlike any other" (Bernstein 1991, translated into English, Latash and Latash 1994). But as we know, no machine has the degrees of freedom (static and dynamic) that the living has. The real subject is actually the distinction between living and non-living: machines are repetitive, the living never repeats itself, the living re-creates nature as being constituted by *the different*, not by *the same*. NAB was direct: "manifestations of vital activity" means interaction of the living with the ever-changing world to which it belongs. But vitalism was declared a reactionary view, as was, in the same sense, the Aristotelian *final cause*, i.e., the purposefulness of actions. Yet NAB wrote about the pursuit of goals as they relate to preserving life, and produced the proof of this in his experiments.

On account of ideological reasons, the Soviet Union censors blocked any thought not aligned with the official dialectic materialism, even when authors – Bernstein, in particular – openly subscribed to it, or claimed to do so. Science in the West was not subject to censorship in the sense of making it impossible to disseminate ideas not aligned with the ideology of those in power – i.e., the scientific establishment. Nevertheless, a healthy scientific debate on the nature of life was for all practical purposes made impossible. Rosen's *Life Itself* (1991) was published, but met with what the Germans call *Stillschweigen* (tacit silence), i.e., the silence adopted by a community of researchers and academics who know who butters their bread. The same happened to the work of Walter Elsasser, a distinguished physicist who would have received his Nobel Prize were it not for his writings of a new foundation of biology. The research of anticipation, definitory of the living, was and still is affected by the same attitude. In view of our justified expectation that this translation of Bernstein's book will be conducive to the reevaluation of many views on the motoric, it is justified to dwell, shortly, on how science is advanced in our society.

The expectation of profitability is implicit in the specific determinism of capitalism. The so-called socialist society (the Soviet Union and the countries aligned with it) cared more for ideological correctness than for an effective science. Capitalist society sees no value in ideology. But for all practical purposes it turns science into a marketable commodity: it monetizes its concepts. With this in mind, it becomes clear why a science that contributes to ever higher profits is preferred, and accordingly supported (by government as well as by business). The quick fix and ever faster machinery have a higher return on investment than living processes do. Treating a chronic migraine with analgesics is a form of reactive medicine. The pill is like the hammer to those who see every problem as a nail. But there are migraines that just won't go away – hammer (all kinds of pills) or not. Incremental medicine, as Atul Gawande labeled it (2017) yields no return on investment, even if it is the only effective medicine. "We devote vast resources to intensive, one-off procedures, while starving the kind of steady, intimate care that often helps people more. Natural processes unfold at the rhythm of life. Evolution, grounded in the anticipatory nature of the living, is steady, but slow. A knee or hip or shoulder replacement will return the person subject to surgery to productive life in a short time. There is a lot of profit in investing in the technology

of replacements – monetizing pain and opioid addiction prove the point. In accord with (bio) physics, an anticipation-based healing procedure (such as genetic repair) will take as long as the deterioration process took (Nadin 2018b). But the outcome – motion, mobility – will be natural and sustainable (a replacement part will not be needed, as is the case with the prosthesis). These are, of course, only marginal thoughts along the line of highlighting NAB's perspective and why it is not so certain that he would have succeeded better in the USA of today than he did in the Soviet Union of pretty dismal memories. It might be the case that what the Soviet regime was not prepared to accept as a breakthrough in science will face similar obstacles in the "free world," but for reasons different from those that made NAB's activity so difficult. However, the real challenge is to continue in the spirit of his broad views in order to avoid the drawbacks of reactive medicine, and of reactive science.

In the Spirit of Bernstein's Perspective

We are a bit ahead of ourselves. In reality, the thought just articulated is the outcome of pursuing NAB's research agenda, but within a context of many new ways to formulate questions, articulate hypotheses, experiment, and eventually advance new ideas. Even if the dominant forces at work in our society are rather focused on more lucrative avenues (such as BCI research already discussed). It is in this context that in 2004, yet another "repetition without repetition" occurred: The Institute for Research in Anticipatory Systems (initiated in 2002) became part of the University of Texas at Dallas. From the broad research agenda, human action took center place. The project *Seneludens* (Nadin 2005) focused on how aging and anticipation expression through action are affected as we get older. Instead of documenting – as did NAB, and Marinescu tried before him – various forms of movement deterioration in the aging, the Institute's researchers asked questions that involved more than anatomy and physiology. We considered the muscular, skeletal, nervous, and even gastrointestinal systems. As a result, we came to associate actions and performance.

The AnticipationScope™ (Figure C3.5) can be considered a development in the spirit of NAB's kymocyclographic method. But that is as far as the connection goes. The focus on quantifying motion changed from aging to performance in general, and what makes other connections possible. NAB worked with athletes; we hosted members of the Olympic gymnastics team, but also golfers and tennis players. He famously analyzed piano playing (1926–1937; Bernstein and Popova 1930) of distinguished soloists (although the experiments were quite crude); we made our own attempt at the same, trying to capture the motion of the entire body playing the piano, and later when a person is engaged in activity of an aesthetic intent (Figure C3.6).

As long as the positivist premise, which informed NAB's experiments as well as ours, was disclosed within the deterministic view in firm control in today's science, there was sufficient funding and institutional support. But the broader agenda of understanding anticipatory processes as definitory of the living could not overcome what NAB and, later on in history, Robert Rosen or Walter Elsasser encountered. Indeed, the revolution in Bernstein's thought is in the anticipatory perspective. There is, of course, no vitalism to detect. The understanding of life as different from the non-living (physico-chemical reality) does not imply such forces, but rather accounts for the fact that biology and physics are not reducible to each other. Take only NAB's "principle of equal simplicity." It is derived from an understanding of motion that is the outcome not of mechanistic control forces, but rather of self-organization driven by the goal of the action. In our research, we

FIGURE C3.5 From Bernstein's kynocyclographic method to the AnticipationScope.

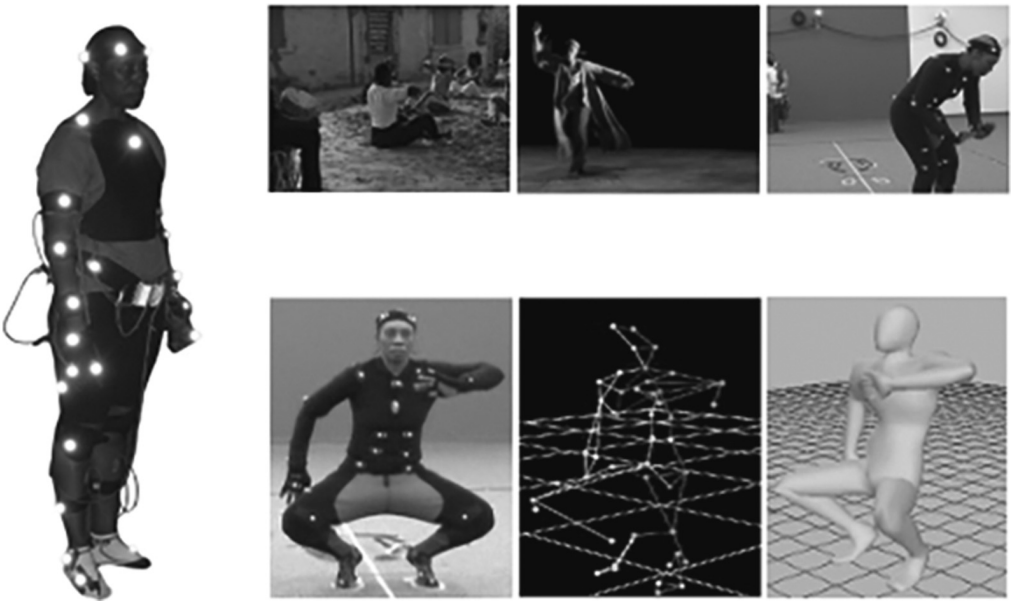


FIGURE C3.6 Capturing movement of aesthetic intent. Germaine Acogny, the "mother" of modern African dance, suggesting movement of therapeutic nature.

documented how the possible future – let's say pregnancy in its various phases – affects the current state of a pregnant woman's anatomy. For example: her skeletal system changes ahead of the added weight and modified body geometry.

Bernstein had success in advancing the idea of a model of the future. Rosen (1985) worked on a definition that is Bernsteinian through and through:

> An anticipatory system is a natural system that contains an internal predictive model of itself and of its environment, which allows it to change state at an instant in accord with the model's predictions pertaining to a later instant.

What neither afforded was 1) to deconfound anticipation from probability; 2) to advance the understanding that anticipatory processes are holistic: they engage the entire organism. Thus they are non-deterministic by necessity. Understanding motion on account of the awareness of anticipation is different from the mechanistic perspective that still dominates research.

The Journey of Discovery Continues

The book, *The Construction of Movement*, finally translated into English was only a preliminary report on a very ambitious scientific endeavor. NAB continued his dedicated inquiry, insisting on the need to find better ways to describe movement and associate it with the purposes triggering

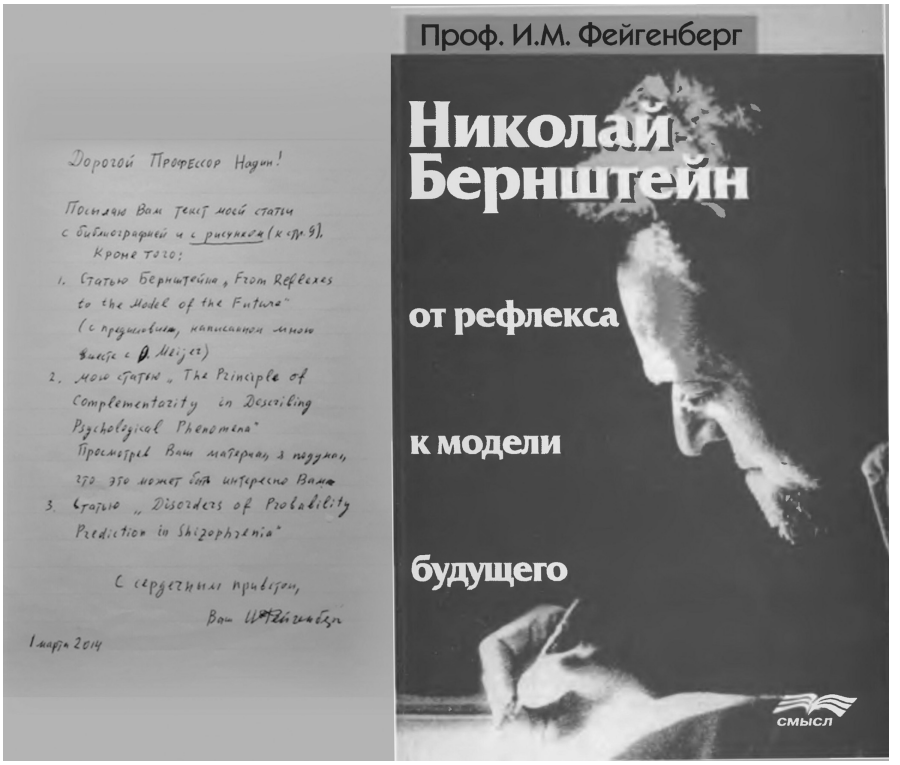


FIGURE C3.7 Learning with and from I.M. Feigenberg: Николай Бернштейн: от рефлекса к модели будущего» – М.: Смысл, 2004. His monograph about NAB.

it. Iosif M. Feigenberg, whose dedication to NAB cannot be emphasized enough, inspired him to address the future in terms of probability. I benefited from interactions with Feigenberg and from reading his book on Bernstein's physiology of movement (Figure C3.7).

We were supposed to meet at the workshop I dedicated to the Soviet/Russian forerunners of anticipation, but it was not to be. In some of my messages to him, I tried to explain why the probability view he suggested to NAB is inadequate for describing the possible future, quite different from the probable future. After all, nothing is probable unless it is possible, but not everything possible is probable.

Probabilities reflect what we don't know about a process: "10% chance of rain" actually means 90% lack of knowledge of those processes that result in precipitation, or lack of it. While deterministic processes have a well-defined phase space (i.e., constant number of variables at work), living processes continuously generate new phase spaces. Let us recall only the example of pregnancy mentioned above. Skeletal changes (spine configuration) are part of the larger phase space. Anticipation, for instance, is expressed in the secretion of oxytocin (which partakes in triggering birth contractions, but also eases the pain of the nipple once the newborn starts to suckle). Prolactin is secreted in advance of lactation, stimulating the mammary glands. On account of such observations, a very simple principle was stated and experimentally confirmed in studies of motion in general: *Anticipatory processes are always expressed in action*. Motoric expression is a realization not within a well-defined path to which quantitative descriptions can be associated, but rather along choices continuously redefined, along a multitude of possible paths. The physics (or chemistry) of life – subject to gravity, we still fall down; we need to touch (apply pressure) to the piano key in order to generate a sound; the physical properties of our ears or eyes are prerequisite to hearing and seeing – is quite well described and explained by physics (or chemistry) using quantitative descriptions. Elsasser thought that Niels Bohr's concept of complementarity: "two different sets of order for inanimate and for living things" would embody a "generalized complementarity" (1998, p. 144). The "two types of order" that "exist in the world" are such that "they never contradict each other." And he drew the following conclusion:

> conventionally designed experiments cannot teach us anything beyond the fact that organisms are physio-chemical systems. *If the holistic properties are to be verified experimentally*, a different type of experiment from that conventionally used *by physicists and chemists* are required.
>
> *(1998, p. 148)*

Chances are that NAB would have agreed with him and worked toward facilitating such experiments. The biology of life is about quantities, but also about *meaning*. Feigenberg was genuinely interested in the dialog regarding such thoughts, and indicated to me that NAB was aware of the need to find better ways to scientifically describe life (Figure C3.8).

NAB's "essential" and "nonessential" variable reflected his focus on "future requirements," and "of that which is not yet, but which must be the case" (Bernstein 1967 p. 187). He, again famously, described a reality we still face in respect to understanding that some goal-oriented actions are successful, while others will fail. This is the non-deterministic aspect, which for those who are given to the theology of the machine (never failing!) remain inscrutable: "Biologists understand the problem but lack the mathematical skills, and mathematicians have the skills, but don't understand the problem," (Bernstein 1965/1988, p. 246). It turns out that Gelfand, among others, argued for a mathematics of life different from the mathematics within which he became famous for his contributions. In an attempt to describe Leonardo da Vinci's intuitive description of anticipation, I made use of "a mathematics of generatively structured entities" advanced by Lev Goldfarb (and some of his collaborators; Goldfarb and Golubitsky 2001). Within this mathematics, the "formative

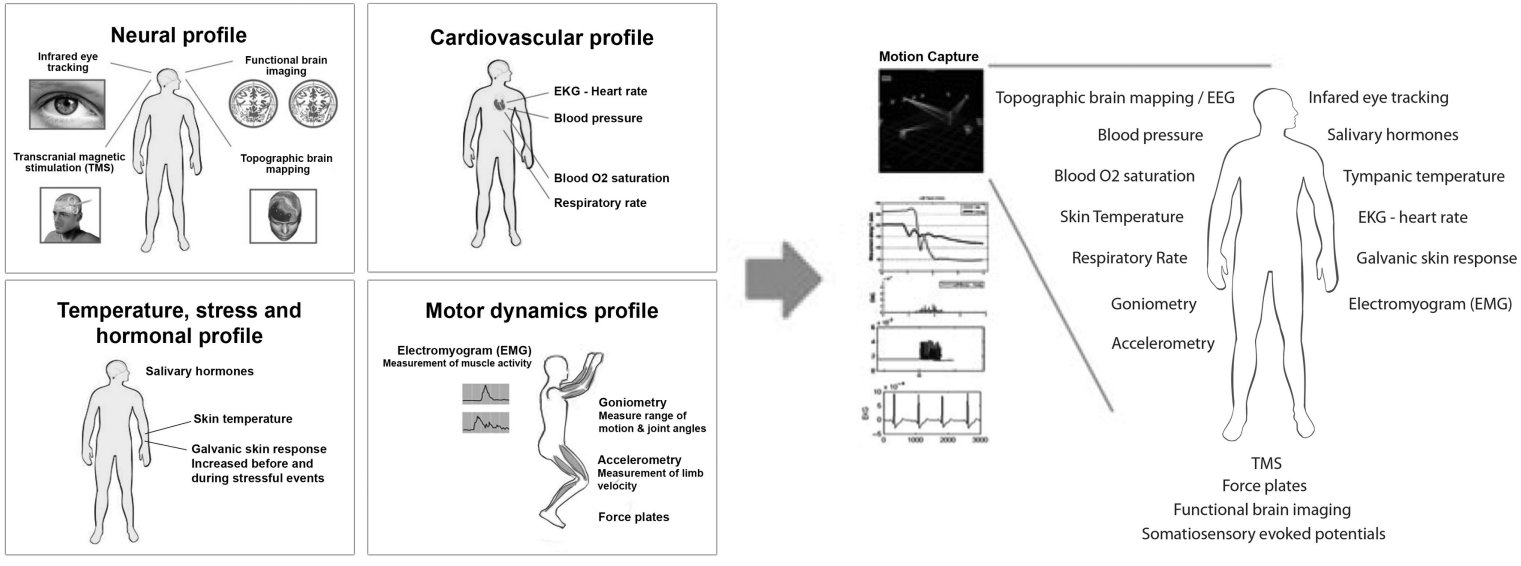


FIGURE C3.8 The Anticipatory Profile reflects the holistic nature of living processes.

evolution, i.e., the constructive path," is of central focus. A structural measurement process – by necessity continuous – replaces the discrete method of associating numbers to positions in space and time. Out of respect for Bernstein's legacy, I shall provide some details of this attempt, very much in the spirit of his inquiries.

Leonardo da Vinci (*Trattato della Pittura*, 1498) took note of what we experience during our actions:

> when a man stands motionless upon his feet, if he extends his arm in front of his chest, he must move backwards a natural weight equal to that both natural and accidental which he moves towards the front.

Over time, this observation caused many to wonder how the act of readjusting takes place. It is, like many other actions, an expression of autonomous processes. Addressing postural adjustment (Gahery 1987) proved that the compensation that Leonardo da Vinci noticed – the muscles from the gluteus to the soleus tighten as a person raises his arm – slightly *precede* the beginning of the arm's motion. In short, the compensation occurred in anticipation of the action. Gahery further took note of the fact makes it clear that every action (movements, tasks performed, etc.) involves "purposive" and "non-purposive" movement. This applies to postural adjustments (involving postural preparations, accompaniments and reactions), or to gait dynamics, for example. Without making reference to NAB's work, and, obviously, not having read *The Construction of Movements*, Gahery confirmed Bernstein's experimental results. With the AnticipationScope, we went further, addressing actions (such as catching a ball, moving on an unstable path, motions associated with stepping into a car, among others) that in the absence of anticipatory behavior could harm those carrying them out. The simple action of taking a seat – e.g., how high, how soft or rigid, how warm or cold, how slippery – involves a multitude of adjustments, all autonomous in nature.

The Anticipatory Profile (Nadin 2012) we derived, using mathematics of generatively structures entities, account for the anticipatory components of our actions – even when they are not purposive. Synergy comes into expression, as well as agonist (supportive) and antagonist (opposing)

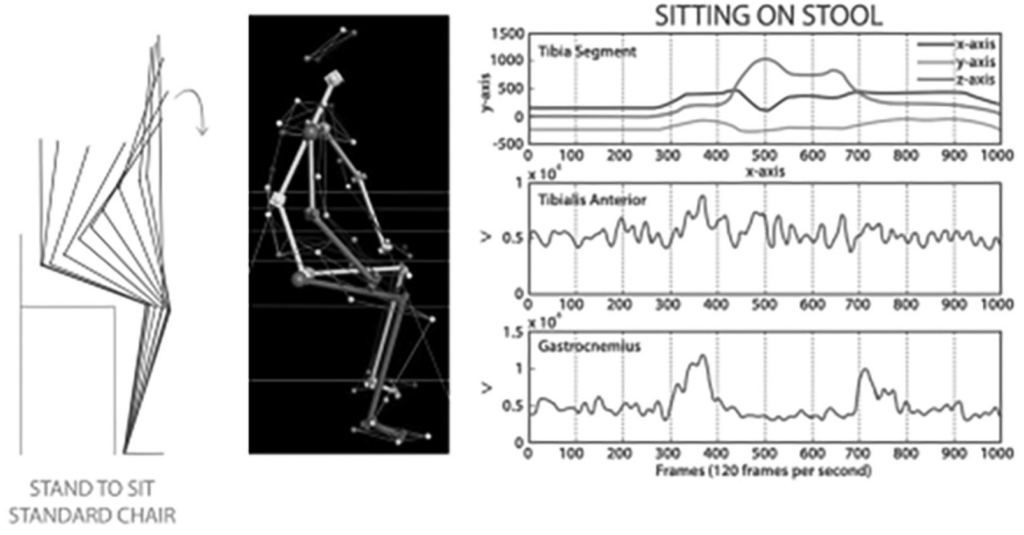


FIGURE C3.9 Anticipation expression in stand-to-sit motoric expression

factors. Without anticipation, we would fall when we raise our arms. Or we would either destroy our chairs (imagine a weight equal to that of a human being falling on a chair) or hurt our backs and buttocks (Figure C3.9).

Where is NAB when one needs him, or someone like him, most? *The Construction of Movements* in English places Bernstein among those who are dedicated to a better understanding not only of how the motoric system functions, but actually of how life is lived. Will they put in the effort needed to understand him?

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