

## **Bernstein's Revolution in Movement Medicine: Coordination Disorders and the Recovery of Walking Biodynamics After Cerebrovascular Injuries (1954)**

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The year 1954 found Bernstein in a rather precarious position. In 1950, he had been fired from his job, following anti-Semitic campaigns in Pravda as well as attacks from the neo-Pavlovians because of his alleged reliance on foreign literature and lack of respect for Pavlov's views (Bongaardt & Meijer, in press). After Stalin's death, Bernstein was slowly rehabilitated but never completely. So when he presented his views on the pathology of movement from his "new" position at the Institute of Neurology of the Academy of Medical Sciences, one would have expected him to be extremely careful, accepting the mechanicism that once more was dominant in the Soviet Union. He didn't.

Comparing this 1954 paper on the pathology of movement with his 1936 paper (Meijer & Wagenaar, 1998), one is struck by the clarity of the 1954 argument and the consistency of Bernstein's approach. After the success of *On the Construction of Movements* (1947) and his leap into the unknown with *On Dexterity and Its Development* (written at the end of the 1940s, translated in Bernstein, 1996), Bernstein apparently felt strong enough to approach the pathology of movement as the pathology of coordination, in line with his famous 1935 paper (1967/1935). It is interesting that the earlier pathology paper (Meijer & Wagenaar, 1998), published in the preceding issue of *Motor Control*, was also written after 1935. Apparently, it was not before the end of the 1940s that Bernstein regarded his theory of coordination as really established and started to proceed beyond it. Theoretically, he would do so in the physiology of initiative (cf. Meijer & Bongaardt, 1998); practically, he went into applications that revolutionized the established views.

### **The Notion of "Coordination Disorders"**

One may designate as "movement medicine" all efforts from neurologists, orthopedic surgeons, rehabilitation specialists, physical therapists, occupational thera-

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pists, and the like to understand, diagnose, and treat movement disorders. Movement medicine shares with every other (para)medical discipline the challenge to establish efficacy and to produce cost benefits (Hiatt & Goldman, 1994). On top of that, however, movement medicine has a challenge of its own, that is, to develop a relevant language to understand, diagnose, and treat pathological movement.

For centuries, dominant approaches to the pathology of movement have focused on the impairment of particular structures (bones, joints, muscles, nerves, blood vessels), while movement itself has been assessed mainly in terms of localized weakness (muscle force, Newtons) or limitations in the range of movement (amplitude, degrees). Only recently has the international community of movement medicine started to recognize the importance of the functional level that is specific to movement (Jette, 1994), the level that can be understood as the organization and coordination of movements. The potential consequences of this shift are enormous, both theoretically and practically, which is why we propose that Bernstein's 1954 notion of "coordination disorders" was a revolution in movement medicine.

Bernstein was a medical doctor, who developed sophisticated techniques to film movements in the 1920s (cf. Bernstein, 1936), presented a new theory of coordination in the 1930s (1967/1935), popularized his views in the 1940s (1947 & 1996), and went beyond normal coordination in the 1950s and 1960s. Not surprisingly, he was one of the first to investigate pathological gait using film recordings. After studying the gait patterns of healthy young subjects (even children) and elderly subjects, in his 1954 paper he presented an overview of gait patterns of people with neurological disorders. Most of these gait studies were directed at the individual, by necessity as Bernstein argued, because pathological movements are different in different individuals even if they have similar neurological conditions. The overriding concept of "coordination disorders," however, allows for a common frame of reference, a common language to understand and diagnose pathological movements and hence, we conclude, to allow for rational treatment (cf. Wulff, 1970).

In our own group, we have studied the coordination dynamics of pathological gait for about a decade. Wagenaar and Beek (1992), for example, showed that walking velocity is an important control parameter in assessing hemiplegic gait, with gait becoming more normal at the higher velocities. Individuals who have had strokes tend to walk slowly, but even when their gait is corrected for velocity, most of these individuals have a small phase difference between pelvic and thoracic rotation in comparison to nondisabled subjects. Wagenaar and Van Emmerik (1994) evaluated frequency coupling between arm and leg movements in the sagittal plane during treadmill walking of individuals who had had strokes. In the velocity range 0.75/1.0 m/s, some of the individuals displayed the normal transition from locking their arms onto the step frequency to the stride frequency (cf. Van Emmerik & Wagenaar, 1996a). In most of the subjects, however, the frequencies of arm and leg movements on the hemiplegic side were hardly influenced by the systematic manipulation of velocity, while the healthy side revealed the transition mentioned above. In other words, a clear asymmetry between body sides was observed.

In a similar vein, we have attempted to dynamically capture movement patterns of people with Parkinson's disease (Van Emmerik & Wagenaar, 1996b). In a number of subjects, the typical transition upon increasing walking velocity to an out-of-phase relationship between pelvic and thoracic rotation did not occur, and

there was an increased stability in relative phase between pelvis and thorax. These individuals hold their trunks relatively "stiff." Another example of such stiffness was found in subjects with chronic low back pain (C.J.C. Lamoth, 1997). In these and other investigations, as in the work of other groups studying coordination disorders (e.g., Holt, Hamil, & Andres, 1990; Holt, Obusek, & Fonseca, 1996), the study of normal gait and that of pathological gait mutually benefit from each other, as is true in Bernstein's work.

Over the last decade, we have presented the results of our work to practitioners of movement medicine. Almost without exception, the idea of coordination disorders (or "coordination dynamics") has had great intuitive appeal to those who deal with movement pathology in their daily work. Such understanding of movement pathology may allow for a valid evaluation, and then improvement, of diagnostic procedures, as was already Bernstein's aim in his 1954 paper. As to intervention studies, we hope it will also be possible to develop and use dependent variables that are sufficiently sensitive to establish efficacy. In the world of movement medicine, intervention studies often show disappointing results (e.g., Basmajian & Gowland, 1987). Part of that problem may be the lack of an appropriate language to capture movement pathology, to diagnose disorders, and to evaluate treatments. While inaccessible to the international community until now, Bernstein's 1954 paper shows how dedicated he was to solving this problem. His notion of coordination disorders was certainly a major step in the right direction.

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## Coordination Disorders and the Recovery of Walking Biodynamics After Cerebrovascular Brain Injuries<sup>1</sup>

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1. Until now, there have been no detailed analyses of coordination disorders<sup>2</sup> of walking and the recovery of walking in organic brain disorders. Contemporary literature demonstrates only a few single attempts to address this issue (Marinesco, Kekcheev, Verbov).

2. The dynamically stable coordinative structure of normal walking represents an integral coordination process, precisely and reliably developed in ontogenesis, defined by both the anatomical (biomechanical) structure of the movement organs and the entire physiological dynamics of internal and external forces progressing under the control<sup>3</sup> of the highest levels of the central nervous system. The influence of the former factor is manifested as the deep interplay of dynamic processes within the whole peripheral apparatus and also as the exceptional stability<sup>4</sup> of subsequent step cycles during normal walking and the very small variability of this act in different healthy individuals (Bernstein, Popova, Spielberg).

3. The facts mentioned above lead one to expect, even in unilateral central injury (hemiparesis), the emergence of coordination disorders in all the links of the motor apparatus, on both sides of the body, and during all the successive phases of walking.<sup>5</sup> These disorders may be expected to reveal themselves as (a) violations of the stability of the dynamical structure in subsequent steps and (b) the

emergence of stable but pathologically changed walking structures witnessing compensational changes in coordination.<sup>6</sup> All these phenomena have been observed in our studies.

4. We filmed a total of 28 patients. Fifteen patients with hemiparesis following a cerebrovascular accident were filmed repetitively, and their data were subjected to detailed cyclogrammetrical analysis.<sup>7</sup> Their ages ranged from 28 to 62 years, the time from stroke to the first study from 2 weeks to several years.

5. Comparative analysis revealed coordination disorders, of different degrees of severity, in all studied parts of the body, both on the affected side of the body and the contralateral (“healthy”) side.<sup>8</sup> Particular features of these disorders, in many cases, allowed us to identify them with paresis of a specific muscle group, that is, with a spastic or, conversely, hypotonic state. These features also let us classify the disorders as primary or compensatory-adaptive.

6. Nevertheless, we have observed a wide variety of disorders that do not allow for, or even suggest, classification. Within each patient, the disorder preserves its characteristic features throughout rehabilitation.<sup>9</sup> The kinds of disorders that are typical to the “healthy” side are, as a rule, different from those on the affected side. While symptoms suggesting an injury to the other half of the brain were diagnosed clinically in only two cases, biodynamic deviations from normal behavior were revealed by the cyclogrammetric analysis in all patients except the two who were least affected.<sup>10</sup>

7. Disorders of normal coordination on the unaffected side partly display a character that is clearly compensatory (for example, an increase of the stance phase of the “healthy” leg as compared to the paretic leg, together with a dramatic increase in the swing velocity of the “healthy” leg). They also show secondary pathological deviations from normal patterns (for example, major anomalies of muscle tone<sup>11</sup> in muscles controlling the knee joint).

8. Analysis of deviations from normal behavior in the movements of the affected leg has led to the identification of a number of signs that can be revealed even by a superficial cyclogrammetric analysis. These signs allow us to diagnose and, to a certain degree, quantify the presence and severity of the paresis or muscle tone disorder in the muscle groups that control each leg joint. This analysis has demonstrated that disorders of coordination and muscle tone can be seen during walking in more than half of the cases studied, even when clinical examination suggests that both paretic and tone disorders have disappeared.

9. The facts described suggest that (a) when muscle tone is assessed with passive movements, it behaves differently from when it is assessed during functional loading of the limb during a coordinated motor act,<sup>12</sup> and (b) patients who during the acute stage of spastico-paretic disorder develop a certain dynamical structure of walking, as accessible to them, have major problems modifying this structure, even when their improved motor resources allow them to switch to a more normal coordinative structure.<sup>13</sup> During this period of improvement we noticed that such a perseveration of an earlier developed dynamic structure can be overcome by the patient with consciously controlled exercise, focusing the patient’s attention on his or her movements.<sup>14</sup> Therefore, during the period of reduction or complete elimination of clinical–pathological signs, it makes sense to substitute or at least supplement exercise of separate muscle groups during physical therapy with a whole-body, consciously controlled, active exercise designed to reorganize and normalize walking.<sup>15</sup>

10. Despite the small number of patients studied until now, the various patterns that we observed gave us the opportunity to clearly differentiate signs of pathological disorder from individual nonpathological deviations. Signs of pathological disorder are characterized by a much higher reproducibility, an obvious decline in the course of motor rehabilitation, and clear asymmetry. Even now, these signs allow one to identify very sensitive symptoms that can be seen during cyclogrammetric analysis even in very light cases of central hemiparesis.

## Notes

<sup>1</sup>The paper was translated by Mark L. Latash and edited for clarity. It was originally published in *Proceedings of the VII Meeting of the Scientific Institute of Neurology of the Academy of Medical Sciences of the USSR* (pp. 28-30), Moscow, 1954.

<sup>2</sup>As far as we know, the conception of "coordination disorders" was new at the time. It is what we regard as the "revolution" in our title.

<sup>3</sup>This notion of "supreme control by the highest level" remained part of Bernstein's theory of movement behavior from 1935 (1967/1935) onward. In Bernstein's view, contrary to what some may have expected (e.g., Reed, 1984), movements were "programmed." Particularly in the later phases of Bernstein's work, this idea of programming turned out to be very different from what would be Keele's (1968) classical formulation. In solving a motor problem, the animal constructs (or chooses) a "highest level" for that particular task. More importantly, in the physiology of initiative, the animal embodies a stochastic model of the future, which then collapses into a single "essential variable" used to control the action-to-be (Bernstein, 1988/1965; Bongaardt, 1996; Meijer & Bongaardt, 1998).

<sup>4</sup>Bernstein failed to specify here that this is a stability of the overall topology of the movement, rather than its metric details (cf. 1967/1935). This underemphasis of the nature of his own theory of coordination may well have resulted from the fact that he was just being rehabilitated and didn't want to disagree too openly with the mechanicism (cf., e.g., Berg, 1963) which was then again dominant in the Soviet Union, after having been forbidden from 1930 through 1950 (Bongaardt & Meijer, in press).

<sup>5</sup>Bernstein's conception of coordination disorders led him to believe that every single aspect of the movement should be different from normal. This ran contrary to the tradition, dominant even today, of translating movement pathology into localized weakness or localized restriction of the range of movement, to be treated by localized physiotherapy exercises (cf. note 15).

<sup>6</sup>For an example of pathological walking being adaptive, see Holt, Obusek, and Fonseca (1996).

<sup>7</sup>Bernstein's technique to film movements—kymocyclography or cyclogrammetry—was developed in the 1920s (cf. Bernstein, 1936).

<sup>8</sup>Even to date, it is relatively unusual to explicitly pay attention to the unaffected side. For a counterexample, see Van Ravensberg (1979).

<sup>9</sup>It is clear that Bernstein wanted to focus on the individual subject. In contemporary movement medicine, it is often stated that patients are "too heterogeneous" to expect a significant effect in randomized clinical trials (e.g., Basmajian & Gowland, 1987) and that one should focus on the individual instead (e.g., Wagenaar et al., 1990). In occupational therapy, this emphasis on the problems of the individual has become paradigm (cf. Ottenbacher, 1986). Thelen's program to understand the early development of coordination as an individual challenge, different for different children (Thelen & Corbetta, 1994), is conceptually similar to Bernstein's 1954 understanding of the importance of specific individual characteristics.

<sup>10</sup>Bernstein observed that his diagnostic system was more sensitive than the usual methods, long before sensitivity became a central issue in medicine (Wulff, 1976).

<sup>11</sup>To Bernstein, muscle tone represented a special level of the organization of movement (cf. Bernstein, 1996), embodying the “preparedness” of the animal (cf. Meijer & Bongaardt, 1998, note 14). The level of “anomalies in tone” is certainly related to that of “paresis” but can, in Bernstein’s view, be functionally distinguished.

<sup>12</sup>The relevance of the functional context of a movement was one of the most important consequences of Bernstein’s theory of movement for understanding pathology (cf., e.g., Leontjew & Zaporozhets, 1960).

<sup>13</sup>In movement medicine, it has remained important to establish when exactly one should allow the patient to move in whichever way possible and when exactly the patient should focus on relearning a “normal” pattern. In treating individuals with strokes, for instance, it was found that initial inhibition of “pathological movements” may slow recovery (Wagenaar et al., 1990). On the other hand, Lamoth (1997) described patients with chronic low back pain who walk as if in acute pain when allowed to walk slowly (hardly any rotation in the spine) but who walk much more normally when asked to go faster; in such individuals, pathological coordination can and should be unlearned.

<sup>14</sup>Also in modern literature, this process of “relearning a normal pattern” or “unlearning a pathological pattern” (cf. note 13) is regarded as a process that, at least initially, requires conscious attention (Mulder & Geurts, 1993).

<sup>15</sup>Bernstein remained relatively modest in his assessment of physical therapy directed at “separate muscle groups.” In fact, his own views may well lead to the conclusion that active, whole-body exercises should be the rule rather than the exception in treating individuals with coordination disorders (cf., e.g., Wagenaar & Meijer, 1991-1992).

## References

- Basmajian, J.V., & Gowland, C.A. (1987). The many hidden faces of stroke: A call for action. *Archives of Physical Medicine and Rehabilitation*, *68*, 319.
- Berg, A.J. (1963). Cybernetics and progress in science and technology. In A.I. Berg (Ed.), *Biological aspects of cybernetics* (pp. 7-24). Washington, DC: US Department of Commerce, Office of Technical Services.
- Bernstein, N.A. (1936). Die kymocyclographische Methode der Bewegungsuntersuchung [The kymocyclographic method of movement analysis]. In E. Abderhalden (Ed.), *Handbuch der biologischen Arbeitsmethoden* (Vol. 5, pp. 629-680). Berlin: Urban und Schwarzenberg.
- Bernstein, N.A. (1947). *O Postroenii Dvižēnii* [On the Construction of Movements]. Moscow: Medgiz (in Russian).
- Bernstein, N.A. (1967). The problem of the interrelation of coordination and localization. In N.A. Bernstein, *The co-ordination and regulation of movements* (pp. 15-59). Oxford, UK: Pergamon Press. (original work published 1935)
- Bernstein, N.A. (1988). Auf den Wegen zu einer Biologie der Aktivität [On the road toward a biology of activity]. In L. Pickenhain & G. Schnabel (Eds.), *Bewegungsphysiologie von N.A. Bernstein* (2nd ed., pp. 233-247). Leipzig, Germany: Johann Ambrosius Barth. (original work published 1965)
- Bernstein, N.A. (1996). On dexterity and its development. In M.L. Latash & M.T. Turvey (Eds.), *Dexterity and its development* (pp. 3-244). Mahwah, NJ: Erlbaum. (original work written in 1947 and published in 1991; translated by M.L. Latash)
- Bongaardt, R. (1996). *Shifting focus: The Bernstein tradition in movement science*. Unpublished doctoral dissertation, Vrije Universiteit, Amsterdam.

- Bongaardt, R., & Meijer, O.G. (in press). Bernstein's theory of movement behavior: Historical development and contemporary relevance. *Journal of Motor Behavior*.
- Hiatt, H., & Goldman, L. (1994). Making medicine more scientific. *Nature*, **371**, 100.
- Holt, K.G., Hamill, J., & Andres, R.O. (1990). The force-driven harmonic oscillator as a model for human locomotion. *Human Movement Science*, **9**, 55-68.
- Holt, K.G., Obusek, J.O., & Fonseca, S.T. (1996). Constraints on disordered locomotion: A dynamical systems perspective on spastic cerebral palsy. *Human Movement Science*, **15**, 177-202.
- Jette, A.M. (1994). Physical disabled concepts for physical therapy research and practice. *Physical Therapy*, **74**, 380-386.
- Keele, S.W. (1968). Movement control in skilled motor performance. *Psychological Bulletin*, **70**, 387-403.
- Lamoth, C.J.C. (1997). Unpublished data.
- Leontjew, A.N., & Zaporozhets, A.V. (1960). *Rehabilitation of hand function*. London: Pergamon Press.
- Meijer, O.G., & Bongaardt, R. (1998). Bernstein's last paper: The immediate tasks of neurophysiology in the light of the modern theory of biological activity. *Motor Control*, **2**, 2-9.
- Meijer, O.G., & Wagenaar, R.C. (1998). Bernstein's rejection of Braune and Fischer: Studies on the physiology and pathology of movements (1936). *Motor Control*, **2**, 95-100.
- Mulder, T., & Geurts, A. (1993). Recovery of motor skills following nervous system disorders: A behavioural emphasis. *Baillières Clinical Neurology*, **2**, 1-13.
- Ottenbacher, K. (1986). *Evaluating clinical change: Strategies for occupational and physical therapists*. Baltimore: Williams & Wilkins.
- Reed, E.S. (1984). An outline of a theory of action systems. *Journal of Motor Behavior*, **14**, 98-134.
- Thelen, E., & Corbetta, D. (1994). Exploration and selection in the early acquisition of skill. In O. Sporns & G. Tononi (Eds.), *Selectionism and the brain* (pp. 75-102) (*International Review of Neurobiology*, Vol. 37). San Diego, CA: Academic Press.
- Van Emmerik, R.E.A., & Wagenaar, R.C. (1996a). Effects of walking velocity on the relative phase dynamics in the trunk in human walking. *Journal of Biomechanics*, **29**, 1175-1184.
- Van Emmerik, R.E.A., & Wagenaar, R.C. (1996b). Dynamics of movement coordination and tremor during gait in Parkinson's disease. *Human Movement Science*, **15**, 203-235.
- Van Ravensberg, C.D. (1979). *Symptomatie van het Hemiplegie-syndroom: Een neurologische en psychologische literatuurstudie, aangevuld met explorerend onderzoek* [Symptomatology of the Hemiplegia Syndrome: A study of the neurological and psychological literature, together with an explorative investigation]. Unpublished doctoral dissertation, Vrije Universiteit, Amsterdam.
- Wagenaar, R.C., Meijer, O.G., Van Wieringen, P.C.W., Kuik, D.J., Hazenberg, G.J., Lindeboom, J., Wichers, F., & Rijswijk, H. (1990). The functional recovery of stroke: A comparison between neuro-developmental treatment and the Brunnstrom method. *Scandinavian Journal of Rehabilitation Medicine*, **22**, 1-8.
- Wagenaar, R.C., & Meijer, O.G. (1991-1992). The effects of stroke rehabilitation: A critical review of the literature. *Journal of Rehabilitation Sciences*, **4**, 61-73 & 97-109.

- Wagenaar, R.C., & Beek, W.J. (1992). Hemiplegic gait: A kinematic analysis using walking speed as a basis. *Journal of Biomechanics*, **25**, 1007-1015.
- Wagenaar, R.C., & Van Emmerik, R.E.A. (1994). Dynamics of pathological gait. *Human Movement Science*, **13**, 441-471.
- Wulff, H.R. (1976). *Rational diagnosis and treatment*. Oxford, UK: Blackwell.

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