

Synergies in Health and Disease: Relations to Adaptive Changes in Motor Coordination



This article describes an approach to motor synergies that allows them to be quantified in people with atypical movement patterns during exercise or practice. Within this approach, motor variability may be classified with respect to a task-specific performance variable as “good” (not affecting the variable) or “bad” (changing the variable). The authors review studies of motor synergies in people with typical movement patterns, in people with Down syndrome, in patients after stroke, and in elderly people. Two stages of practice effects on motor synergies are described as being characterized by different changes in the synergy index: an increase followed by a drop in the index. Synergy changes with practice may be accompanied by plastic changes in both descending projections from the primary cortex and interhemispheric projections. The authors emphasize the importance—for practitioners in the area of motor disorders and rehabilitation—of being aware of the latest progress in motor control and coordination. [Latash ML, Anson JG. Synergies in health and disease: relations to adaptive changes in motor coordination. *Phys Ther.* 2006;86:1151–1160.]

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Consider the following axiomatic statement: In order to study a phenomenon, one has to be able to define it and to have tools that can identify the phenomenon or, even better, the tools to quantify it. In the area of the control and coordination of movements, including atypical movements that may be performed by patients seeking help from physical therapists, such tools and definitions are commonly absent. There is not even agreement among researchers on the general principles of motor control. What are the control variables manipulated by the central nervous system (CNS) to produce movements? Are these control variables direct precursors of mechanical variables such as joint torques, as it is commonly assumed in robotics and other fields of control of inanimate objects and as advocated by the ideas of internal models?¹⁻³ Do these variables represent time changes of parameters related to spatial coordinates of muscle activation, as suggested, for example, by the equilibrium-point hypothesis?^{4,5} Without answers to these questions, searching for a means to correct the atypical patterns of these undefined control variables is likely to be futile.

Similarly, there is no agreement on how to address motor coordination. Traditionally, issues of motor coordination have been considered in relation to the notorious problem of motor redundancy.⁶⁻⁸ How does the CNS select particular solutions from the innumerable options afforded by the many effectors (muscles, joints, and limbs) that typically take part in natural movements? Many studies followed Bernstein's idea of the elimination of redundant degrees of freedom (DOFs) and searched for computational principles (commonly involving optimization) that would allow the discovery of such unique solutions (reviewed in Rosenbaum et al⁹ and Seif-Naraghi and Winters¹⁰). Recently, however, an alternative termed the "principle of abundance" has been proposed^{11,12} that suggests that the CNS does not eliminate any DOFs but uses them all to ensure flexible and stable performance of motor tasks. That is, the CNS views the apparently redundant system as abundant and

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prefers to make use of the abundance rather than fight against it. This principle of abundance has encouraged a move toward suggesting a definition and a method of quantitative analysis for one of the central notions in both unimpaired and disordered motor coordination, that of a synergy.

Synergies and the Uncontrolled Manifold Hypothesis

The notion of synergies has been used by many famous researchers^{6,13} for more than a hundred years, and synergy is often loosely defined. We would like to offer a definition that states that a *synergy* represents an organization of elemental variables (DOFs) that stabilizes an important performance variable. *Elemental variables* are the smallest sensible variables that can be used to describe a system of interest at a selected level of analysis. *Performance variables* refer to potentially important variables produced by the system as a whole. For example, the rotation of individual joints may be used as elemental variables in kinematic studies of multijoint reaching, and the coordinates representing the endpoint may be viewed as performance variables. To cite another example: in studies of multifinger actions, neural commands issued to produce force by individual digits may be viewed as elemental variables, while the total force or the total moment of forces produced by the hand may be regarded as a performance variable.

The above definition of synergy is consistent with the principle of abundance and permits the introduction of

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quantitative indices of synergies. A particular computational method to quantify synergies has been represented within the uncontrolled manifold (UCM) hypothesis.¹⁴ The term “manifold” refers to a set of points within a space that are well organized according to certain mathematical criteria. The hypothesis proposes that the controller acts in the space of elemental variables (eg, 7 major rotations shared by the shoulder, elbow, and wrist joints) and selects in that space a manifold (a UCM [eg, sets of angular values that all correspond to a fixed position of the index fingertip]) corresponding to a required value of a performance variable (eg, Cartesian coordinates representing that position of the fingertip pointing at an object). Note that all points within the UCM correspond to perfectly accurate pointing. Then the controller organizes covariation of elemental variables in such a way that most variability is limited to the UCM. Such a mode of control leads to relatively small deviations of the fingertip from the required position in space as compared with what could be expected if all joint angles varied independently. That is, the controller exerts little control over elemental variables as long as they stay within the UCM (thus, the term “uncontrolled”) while it tries to bring them back to the UCM if they deviate from it.

Variability is always present in all human movements. What the UCM hypothesis suggests is that variability can be “bad” (VBAD) (affecting an important performance variable and causing larger errors) or “good” (VGOOD) (keeping that variable unchanged, maintaining a successful outcome). For example, touch the tip of your nose with your right index finger. Now any changes in the right arm joint angles that do not result in loss of contact between the index fingertip and the nose are “good”: they do not result in failure of the main task, and they allow for flexibility in its performance, with provision, for example, to perform another, perhaps more ecologically valid task simultaneously (eg, pressing on the door handle with the elbow). Changes in joint angles that move the fingertip away from the nose are “bad” because they lead to a change in the important performance variable (the distance between the fingertip and the nose that has to be zero).

We suggest that the main goal of synergies is to try to make most variability “good.” Thus, one can quantify synergies by comparing the proportion of VGOOD in the total variability within the space of elemental variables. Such a comparison has commonly been done across repetitive attempts at a task.^{15,16} Imagine that an individual is walking on a treadmill and that the researcher is going to conduct a treadmill gait analysis. Individual steps may be viewed as consecutive attempts at the task. If, for example, a potentially important variable is associated with location of the center of mass (COM) of the

body within a coordinate system moving with the subject, changes in joint angles at a given phase of the step cycle from one step to another are expected to lead to small changes in the COM location. This hypothesis may be tested by an appropriate comparison of the “good” and “bad” components of joint angle variability across repeated steps.

In recent studies,^{14–20} a particular measure of variability, variance (ie, the squared standard deviation), was compared within the UCM (VUCM) and orthogonal to the UCM (VORT). If $V_{UCM} > V_{ORT}$ (quantified per degree of freedom in each of the 2 subspaces), it can be concluded that a synergy, as defined earlier, exists, stabilizing a performance variable for which the UCM was computed. In contrast, if $V_{UCM} = V_{ORT}$, there is no synergy specific to the performance variable. Several indices have been introduced to quantify the relative amount of VUCM (“good” variance) in the total amount of variance. For example, the ratio of the amounts of variance per dimension in the 2 subspaces, the UCM and orthogonal to the UCM, and the difference between the 2 subspaces normalized by the total amount of variance per dimension in the space of elemental variables. Particular examples can be found in the references mentioned.

One of the attractive features of the UCM method is that it permits the use of a single data set to test the existence and strength of possible synergies involved in stabilization of different performance variables. For example, when a person repeatedly performs a task that involves the production of a certain total force and total moment of force on a fixed object, indices of total force stabilization and total moment stabilization may be computed using the same data from finger forces.^{15,16} That is, the UCM method allows us to perform a quantitative analysis of behavior of a multi-element system and to ask a question: Does a synergy exist with respect to such and such a performance variable in such and such a task?

Note that accurate task performance may be ensured using a stereotypical movement pattern repeated across trials (eg, making absolutely identical steps accompanied by identical rotations in all the major joints). Such a pattern would be associated with small variance of the elemental variables, both within and orthogonal to the UCM and, therefore, is likely not to be reflective of a synergy according to the definition we have presented. We will return to this example later, because it emphasizes an important difference between the introduced definition of synergies and the meaning of this word commonly used in clinical practice.

Typically, more than one performance variable needs to be stabilized by a set of elemental variables during

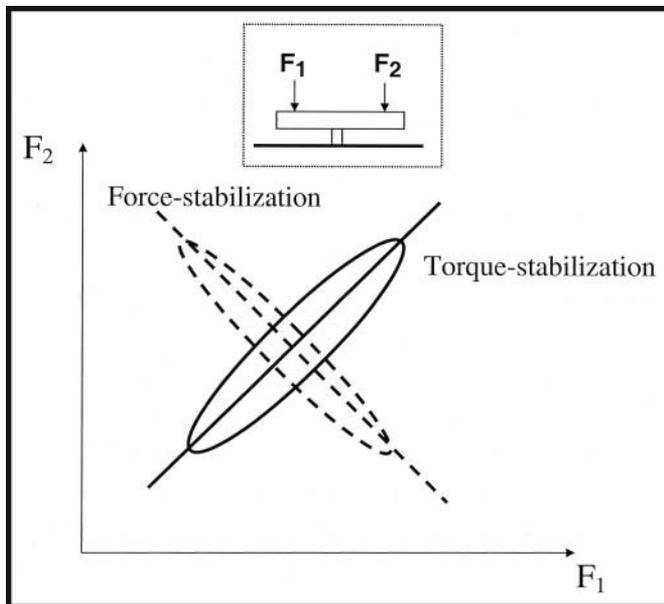


Figure 1.

When a person presses with 2 fingers on 2 force sensors mounted on a frame placed on a narrow support (top insert), the 2 finger forces (F_1 and F_2) may co-vary to stabilize the total force (illustrated with the dashed line with the negative slope) or the total moment of forces with respect to the pivot (illustrated with the solid line with the positive slope). Depending on which variable is stabilized, data point distributions may form 2 ellipses. Note that the 2 performance variables, the total force and the total moment, cannot be stabilized simultaneously.

natural movements. Some of these variables may need to be kept relatively unchanged. Such task components may be addressed as “postural” or “steady-state”—for example, the COM location with respect to the support area in a standing person or the orientation of a glass filled with water while the glass is being moved to the mouth. Variables characterizing other task components, such as responses to unexpected perturbations during goal-directed tasks, may need to change rather quickly. The steady-state performance variables apparently benefit from strong synergies that stabilize their values. This is not true for quickly changing variables, because synergies act against their changes. For example, a strong synergy stabilizing the vertical trunk orientation may be desirable during standing. It may not be desirable during a diving competition.

Performance variables may compete with each other such that stabilizing one of them may lead to destabilization of another. Some of the issues associated with the relationships between synergies and steady-state performance variables and between synergies and rapidly changing performance variables have been addressed experimentally; others are still waiting to be explored. Imagine a very simple situation (Fig. 1): A person presses with 2 fingers on a wooden block placed on a narrow pivot exactly in the middle between the 2 fingers. If the person wants to stabilize the total force produced by the

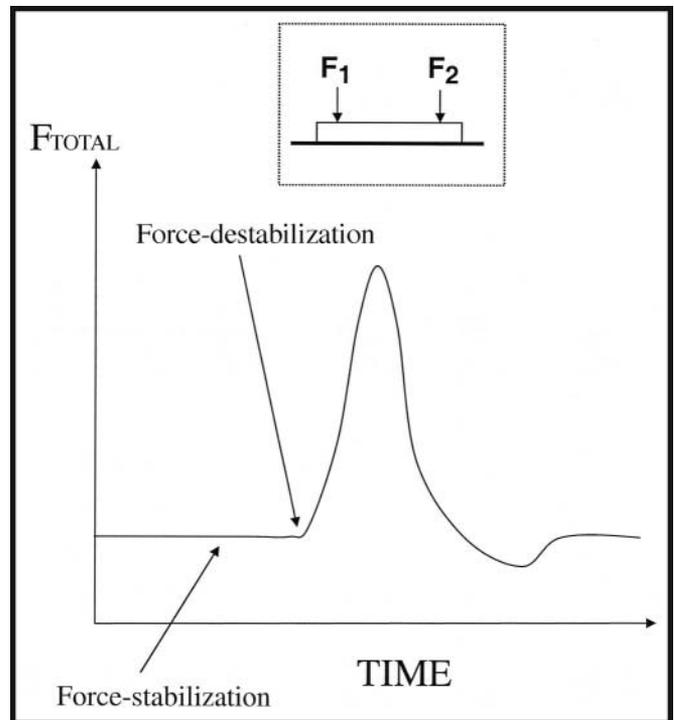


Figure 2.

When a person produces a quick force pulse from a certain steady-state level of the total force (F_{TOTAL}), total force stabilization is observed during the steady-state force production. It is substituted by force destabilization immediately prior to and during the quick force change. Synergies can be modified in preparation for an action. The top insert shows the points of force application by the 2 fingers.

fingers, the 2 finger forces should co-vary negatively (ie, if one of them increases, the other should decrease). In contrast, if the person wants to keep the balance of the plank on the pivot, the 2 forces should co-vary positively (ie, if one of them goes up, the other should go up as well). Thus, the requirements for force stabilization and balancing the plank are incompatible: variability that is “good” for force stabilization is “bad” for moment stabilization and the other way around so that the 2 synergies cannot coexist.¹⁷ How does the CNS solve this problem? Is it possible that solutions differ across typical and atypical subpopulations?

Now imagine another simple situation: A person presses with 2 fingers on force sensors and tries to maintain a certain level of the total force constant. As already mentioned, the 2 finger forces should co-vary negatively. Now imagine that the person wants to change the force very quickly (Fig. 2). To do this, both finger forces should increase simultaneously. However, the force-stabilizing synergy would try to prevent this from happening. Apparently, it needs to be turned off (and maybe reinstated after a new level of total force is achieved). Recent studies^{18,19} have shown that the CNS can indeed start turning a synergy off in anticipation of a planned quick action. This nontrivial ability of the CNS

to change synergies without changing the overall output of a multi-element system is likely to be of major functional importance, providing for movement economy and flexibility. Recent observations have suggested that this ability is impaired in elderly people (Olafsdottir et al, unpublished research). This ability also may be impaired in patients with neurological disorders.

The introduced definition of motor synergies and the associated methods of analysis may be applied to movements of people who show apparently suboptimal motor patterns such as those observed in patients with neurological disorders, people with atypical development, and elderly people who are healthy. In one of the groups studied, the data collected in people with Down syndrome²⁰ were analyzed using UCM analysis, not across a set of trials, but across samples collected during a single trial.¹⁶ Such analysis is possible for certain tasks characterized by unchanged relationships between changes in elemental variables and in performance variables. For example, within-trial UCM analysis can be easily applied to multifinger synergies stabilizing the total force because the total force is always the sum of forces produced by individual digits. In contrast, such analysis cannot be directly applied to analysis of multijoint synergies stabilizing endpoint trajectory because endpoint coordinates are expressed via trigonometric functions of joint angles such that these expressions change their values at different joint configurations. This extension of the method is potentially important for studies of atypical populations, including clinical studies, because many patients cannot be realistically expected to perform dozens of trials under an unchanged control strategy.

Coordination Impairments in Patients After Stroke

People who have experienced a stroke are described clinically as having abnormal movement synergies, typically characterized as relatively fixed or stereotypic,^{21,22} based on analyses of the patterns of how the muscles change their activation levels or the joints change their position during the execution of particular tasks. In this context, the word “synergy” means something like “variables that change together.” This meaning is rather different from the definition introduced earlier. Parallel scaling of elemental variables may reflect not a control strategy but other factors. For example, when objects of different weights are placed on the top of the table, forces under all 4 legs of the table change proportionally. However, we would not like to describe a table as a synergy of its 4 legs; otherwise, any inanimate object would qualify for being a synergy (eg, a stone would become a synergy of its parts). To keep the term “synergy” different from “any material object,” it has to be defined in a task-specific way, as described earlier.

Within the UCM method, proportionally large variability within the UCM is a crucial feature of synergies that affords them flexibility. Without a proper quantitative analysis, it is difficult to accept the proposition that an apparently abnormal motor pattern observed in a patient corresponds to a changed synergy.

Reisman and Scholz²³ recently applied the UCM method to re-examine the coordination of reaching in individuals who had sustained a unilateral stroke in their left hemisphere. The participants showed less flexibility in the joint coupling patterns (confirmed by principal components analysis). However, all of the participants showed strong multijoint synergies (ie, $V_{UCM} \gg V_{ORT}$) stabilizing the endpoint trajectory. These multijoint synergies were quantitatively similar to those observed in people who were healthy (no stroke). Although the patients had greater difficulty moving their arms to the required spatial location due to the altered patterns of involvement of the participating joints, their reaching movements still exhibited joint coordination that stabilized the hand path across repetitions.

These results emphasize the importance of analysis of both features of a synergy, sharing and error compensation among elemental variables, in order to get important information about the nature of motor deficits in such patients. By “sharing” we mean the average (across trials) contribution of elemental variables to a performance variable, while “error compensation” refers to coordinated changes in elemental variables from trial to trial that keep the variability of that performance variable low. In a following section on reaching movements after stroke, we mention a finding that indicates major changes in joint contribution (sharing) to hand motion in patients with stroke without a change in an index that quantified how joints were coordinated to ensure an accurate reach (error compensation). In fact, a more recent analysis of reaching involving participation of the trunk revealed that individuals with mild right hemiparesis exhibited poor error compensation when reaching beyond arm’s length, but only when reaching away from the hemiparetic side.²³ Because the weight of the trunk had to be shifted over the hemiparetic side (these patients had difficulty accomplishing this shift), the reaching synergy of their right hemiparetic arm was selectively disrupted.

Impairment of Multidigit Synergies With Age

Aging leads to changes at many levels of the neuromotor hierarchy. In particular, there is a progressive loss of the number of motor units in hand muscles, accompanied by processes of reinnervation, leading to the emergence of larger and slower motor units.^{24,25} These processes also are accompanied by a reduction in muscle force and a general deterioration of hand motor function.^{26,27}

Indices of finger interaction during pressing tasks also are changed with age.^{28,29}

Finger coordination during the task of 4-finger slow ramp force production was analyzed in young and elderly people.³⁰ In this task, the subjects sat in front of a monitor and pressed on 4 force sensors with the fingers of a hand to match the summed output of the sensors with a line corresponding to a steady increase in the total force. Elderly subjects were more variable in their performance. Analysis using the UCM method showed much worse stabilization of the total force-time profile and of the total pronation/supination moment by the elderly subjects. (Despite the fact that the production of the total moment was not an explicit part of the task, earlier studies^{15,17} have shown that subjects do attempt to stabilize the value of this moment even without being instructed to do so.) That is, elderly people showed a much higher proportion of VBAD in the finger force space with respect to both total force and total moment.

When a person is asked to grasp a handle, hold it in the air, and then squeeze it slowly such that the total force increases in a ramp-like fashion with time, there is covariation of the digit forces that is partly necessitated by the task constraints. In such tasks, elderly people are less accurate in the production of both total moment and total force.³¹ Both young and elderly subjects stabilize the total force and the total moment produced on the handle. However, elderly people show lower values of the indices of both force- and moment-stabilizing synergies (lower proportion of VGOOD). Thus, one can conclude that elderly people are impaired in their ability to coordinate individual digit forces and moments to ensure stable performance with respect to the force/moment production tasks.

Stabilization of the gripping force and of the total moment of forces acting on a handheld object is a component of many everyday tasks such as drinking from a glass, eating with a spoon, using a screwdriver, writing, turning a doorknob, and so on. The demonstrated impairment of multidigit synergies that ensure stabilization of those 2 important performance variables in elderly people may contribute significantly to their overall impaired performance in everyday motor tasks.

Multifinger Synergies in Down Syndrome

People with Down syndrome show a wide spectrum of motor abilities. Some individuals with Down syndrome produce movements that are not grossly different from those seen in the general population. However, even these mildly different movement patterns look unusual to an external observer and are commonly addressed as “clumsy,” although their possible adaptive role has been widely discussed (for a review, see Latash^{32,33}). There is

no good definition for “clumsiness.” In lay terms, it means something opposite to “good coordination.” People with Down syndrome take more time to initiate a response to a stimulus (longer reaction time; for a review, see Anson³⁴) and more time to complete a motor task (longer movement time; for a review, see Latash³²) compared with people who do not have Down syndrome. Another conspicuous feature of movements of people with Down syndrome is the preference for patterns of muscle activation characterized by higher levels of co-contraction (reviewed in Latash³³), that is, simultaneous activation of muscle pairs acting at a joint in opposite directions (“agonist-antagonist muscle pairs”).

In a study of the effects of practice on a finger force-production synergy in people with Down syndrome, the participants produced ramp profiles of the total force while pressing on force sensors with all 4 fingers of the dominant hand.^{16,20} The UCM method was used to analyze deviations of finger forces in individual trials from the average across-trial values at each time sample over the task performance. Imagine that one finger in one of the trials, at a certain time over the task performance, showed a force magnitude higher than its average force for that time. If other fingers also show at that time higher forces compared with their average contribution (positive force covariation), the total force will deviate significantly from its required magnitude. In contrast, if other fingers show lower forces (negative force covariation), these changes will compensate, in part, for the effect on the total force of the original deviation introduced by the first finger. The second scenario corresponds to a multifinger force-stabilizing synergy.

Prior to practice in this study,^{16,20} people with Down syndrome showed predominantly positive covariation among individual finger forces that destabilized the total force. These people used a strategy that may be called a “fork strategy.” They pressed strongly or weakly with all fingers as if the fingers were the prongs of a fork. After 2 days of practice, they showed improved covariation of force modes, which stabilized the total force profile. These observations carry an important optimistic message: apparently, in people with Down syndrome, sub-optimal synergies may be improved with practice.

Learning Motor Synergies

We have naturally come to a central issue relevant to motor rehabilitation, that of motor learning. Within this article, we are interested mostly in one aspect of motor learning, that of learning motor synergies.

According to Bernstein’s theory of staged skill acquisition,³⁵ practicing a movement leads to a sequence of changes in the number of DOFs. Early stages of skill

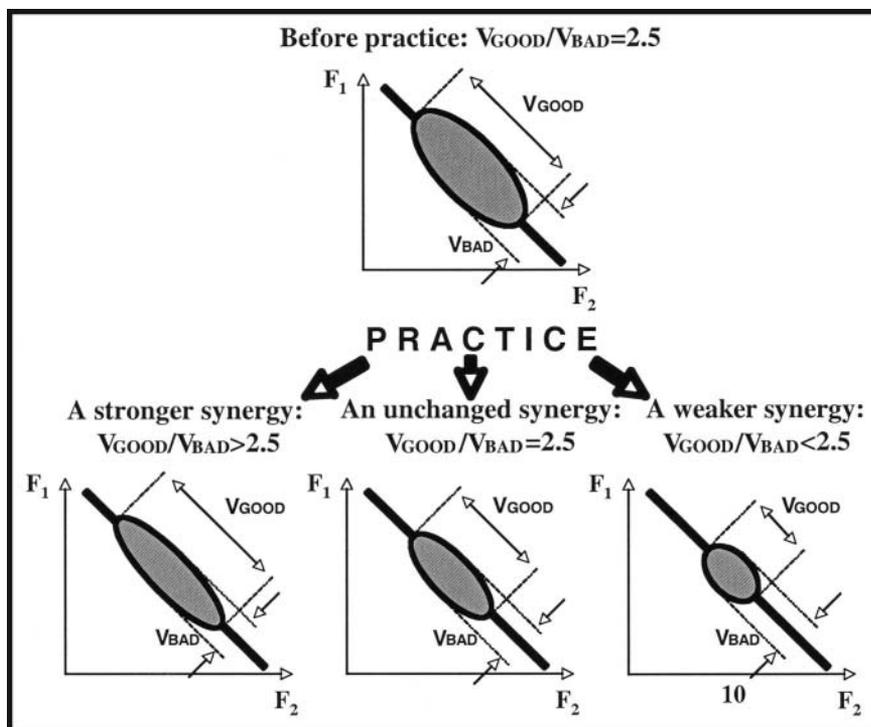


Figure 3.

An illustration of possible effects of practice on 2 components of motor variability, “good” variability (V_{GOOD}) and “bad” variability (V_{BAD}), in a task requiring constant total force production with 2 fingers (similar to the one illustrated in Fig. 1). V_{BAD} is expected to decrease. V_{GOOD} can show no change (left panel, stronger synergy), change proportionally to V_{BAD} (middle panel, unchanged synergy), and change more than V_{BAD} (right panel, weaker synergy).

acquisition are assumed to be associated with a reduction in the number of DOFs, which was assumed to make it easier for the controller to deal with the task, whereas in later stages more DOFs are released or recruited. This view has not been challenged to our knowledge, and some authors^{36,37} have described changes in the number of DOFs with practice. Such claims have been made typically when changes in a particular variable (DOF) became smaller (the variable is considered “frozen”) or larger (the variable is considered “freed” or “released”) with practice.

We would like to emphasize 2 points. First, holding a variable relatively unchanged during a multi-element action is not a trivial task and cannot be associated with “easier control.” For example, keeping a joint of a multijoint effector motionless during a fast movement requires precise modification of control signals to muscles crossing the joint because of the mechanical joint coupling.^{38,39} Second, the number of DOFs (independent variables that describe the system) does not change when one of the variables starts to show smaller or larger variations within a motor task.

When a person practices a task that requires the production of a certain value or a time pattern of a performance

variable (eg, producing a tennis racket trajectory during a serve), it is natural to assume that the practice will result in a decrease in the variability of that performance variable. However, does it also have to result in improved motor synergies? The answer to this question is, “No!” Synergies may be characterized by a quantitative index, for example, the ratio of V_{GOOD} to V_{BAD} or the normalized difference between them (certainly, properly quantified—see Kang et al⁴⁰ and Domkin et al⁴¹). More reproducible performance after practice means that variability that is “bad” (V_{ORT}) has decreased. However, it says nothing about variability that is “good” (V_{UCM}). It may decrease in proportion to the change in V_{ORT} . We would then say that the synergy strength stayed unchanged. However, V_{GOOD} also may decrease to a smaller degree (the synergy becomes stronger) or to a larger degree (the synergy becomes weaker).

Figure 3 illustrates possible changes in V_{GOOD} and V_{BAD} with practice of a task described earlier and illustrated in Figure 1 that requires accurate force production by 2 fingers. All of the “after

practice” panels show a decrease in V_{BAD} . However, they show different changes in the amount of V_{GOOD} that have very strong effects on estimates of force-stabilizing synergies. In the middle panel, both V_{GOOD} and V_{BAD} decreased proportionally. This can be interpreted as more accurate control of each of the finger forces without a change in the synergy. In the left panel, V_{GOOD} dropped less than V_{BAD} ; this can be interpreted as a stronger synergy. In the right panel, the situation is opposite, V_{GOOD} dropped more than V_{BAD} , resulting in a weaker synergy. Experiments have shown that all 3 scenarios are possible.^{40–44}

Experimental studies of the effects of learning of multi-joint pointing tasks,^{41,42} Frisbee throwing,⁴³ and multi-finger force production tasks^{20,40} have shown that effects of practice have 2 stages. The first stage may be associated with learning how to organize changes in individual elemental variables to produce a time profile of an important performance variable. As a person progresses along this route, an increase in the proportion of V_{GOOD} is expected (ie, a synergy emerges and strengthens).⁴⁰ During the second stage, other factors start to play a role such as elaborating a more stereotypical, optimal sharing pattern among elemental variables given a set of constraints and maybe other goals such as comfort, smooth-

ness of trajectory, and so on. This stage may be expected to lead to a drop in the index of synergy by constraining more VGOOD. Both stages have been observed in a single experiment.⁴⁴

Neural substrates responsible for changes in synergies with practice are basically unknown. This is partly due to the paucity of studies that have used both imaging techniques and analysis of the structure of motor variability (in particular, the UCM method) in the same experiment. Two studies^{44,45} applied transcranial magnetic stimulation (TMS) over the primary motor cortex to study possible plastic changes in the CNS over relatively short practice sessions. Both studies showed that changes in TMS induced responses, suggesting changes in both direct corticospinal projections and interhemispheric inhibitory projections with practice. In one of these studies,⁴⁴ the practice session was limited to about 90 minutes. It suggests that plastic changes may happen over very short time intervals (also see Classen et al⁴⁶). That is, the brain is capable of a continuous process of adaptive plastic change.

Are There Lessons for Physical Therapy and Rehabilitation?

Given that there is not even agreement among researchers on the general principles of motor control, we recognize that there is some risk in suggesting associations between the introduced method of quantitative assessment of synergies and clinical practice. However, in taking the risk, we hope that our comments will provide food for thought.

The UCM hypothesis and associated method of quantitative analysis of variability offer the exciting possibility of quantifying synergies at different levels of analysis (eg, kinematic, dynamic, or electromyographic). Until now, the method has been used mostly to quantify the 2 components of variability (“good” and “bad”) and their task- and practice-related changes. By itself, this has been a step forward in analysis of synergies. However, the potential of the method is much broader. In particular, the method has not addressed issues such as possible different patterns of variability within the UCM. By definition, all variability within the UCM is “good”; why should the controller care about this apparently irrelevant variability? Apparently, the controller does care. Results from some studies^{41,44} have indicated that the controller may choose to modify this component of variability. This ability of the controller to use the flexibility afforded by the apparently irrelevant VGOOD may be impaired in people with motor disorders, leading to a diminished capability to take advantage of the flexibility.

The UCM approach is currently at an early stage of development. Until now, most studies used major simplifications and tasks that can be criticized as artificial. The routes to applying UCM approaches to clinical studies face a number of challenges. In particular, although identification of elemental variables may be relatively straightforward in people who are healthy, this essential step in the UCM analysis may pose problems in patients with neurological disorders whose ability to change apparent elemental variables independently of each other may be impaired. For example, a tight coupling between individual joint rotations may lead to a decrease in the number of elemental variables the controller can effectively manipulate. Most studies have used analysis of variability across consecutive trials at a particular task to quantify the 2 components of variance. However, it may be unrealistic to expect patients with neurological disorders to be able to perform many trials using the same control strategy. Development of the UCM method so that it can be used for analysis of single trials or small groups of trials is urgently needed.

Here is a short list of questions that may be potentially addressed using the UCM method in clinical studies:

1. Is there a change in the strength of synergies that contribute to participation in everyday movements such as standing, sit-to-stand, pointing, grasping, stepping, and so on in particular clinical states?
2. If a synergy is impaired, are its changes related to an increase in VBAD (poor control of a performance variable) or a decrease in VGOOD (inability to use flexible solutions)?
3. Can rehabilitation lead to a modification of pathologically changed synergies?
4. Can different rehabilitation approaches be compared quantitatively in their ability to improve synergies?
5. Is improvement in a synergy always associated with better performance of the task?

Earlier, we mentioned 2 studies^{44,45} that used the TMS technique to document plastic changes in neural projections after a relatively brief period of practice. In clinical applications, the beneficial outcome of neural plasticity is emphasized in a demand for compensation to facilitate recovery.⁴⁷ Evidence for structural compensation from neural plasticity is increasing.^{48–50} Relationships between neural plasticity and changes in synergies, as quantified by the UCM method, are nontrivial. Depending on the nature and extent of neurological injury,^{50–52} plastic changes may or may not be able to restore preinjury synergies. In the latter case, creation of new

synergies possibly based on new sets of elemental variables may be expected. The UCM method offers a tool to track processes of emergence of such novel synergies.

Summary

Two significant developments have the potential to reshape thinking about adaptive change in motor coordination: the evolving knowledge of neural plasticity and the development of the UCM hypothesis. Coincidentally, the former development embraces the physiology of the movement system, and the latter development captures to a greater extent the behavior of the system. The challenge in the next decade is for clinical practice, kinesiology, and neuroscience to describe and investigate the interaction between neural plasticity and the ability to create and modify synergies in order to better understand motor coordination and its relationship to rehabilitation practices.

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