Reorganizing Human Motor Behavior through Practice

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Abstract

Skilled human movement is apparently easily produced and highly coordinated despite the high number of degrees of freedom controlled during its execution. Here, we examine the learning of a whole body movement over practice from three levels of analysis: 1) elemental, 2) subsystem, and 3) macroscopic order parameter, with respect to the role of constraints in motor skill acquisition. With practice, the body segments were re-organized to achieve the 3 sub-tasks, namely: 1) a medio-lateral forcing torque, 2) a vertical downward force and 3) an anterior-posterior equilibrating torque. The output complexities of the two subsystems, the forcing (medio-lateral) and equilibrating (anterior-posterior) motions of the center of mass changed in a compensatory manner, increasing or maintaining the stability of the overt behavior. This pattern of findings supports the ideas of dynamical approaches to motor learning and holds interesting parallels to tenets of the Theory of Constraints (Goldratt, 1990) for system (re)organization.

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Human actions are highly coordinated despite the number of joints and limb segments that require control during these actions, more so when these actions are directed toward the achievement of a goal. A high level of organization is necessary as the motor system is essentially redundant, as it possesses more degrees of freedom than it needs to complete any given motor task (Bernstein, 1967). This redundancy results however, in variability in the movements it produces, where even a skilled action, performed repetitively are ever truly identical, despite similarities in the task outcome. This variability affords to the system greater flexibility, allowing it to adapt to environmental demands and acquire new skills. With practice, these degrees of freedom that are available to the motor system are organized and re-organized, often becoming more structured with practice, as the stability of the coordination patterns increases. Within motor behavior, the theory of coordinative structures has proposed that motor actions are emergent properties, arising from the interactions of constraints (Kugler, Kelso, & Turvey, 1980; Newell, 1996). This paper will draw its theoretical approach from a complex systems perspective, analyzing the changes in behavioral outputs at the macroscopic and microscopic levels during the learning a whole body task, seeking parallels from the study of human behavior to other complex systems studied (e.g., large corporations, government agencies) which are also goal-directed, intentional systems.

The acquisition of human motor skills results in the reorganization of the outputs of the many degrees of freedom (joints/body segments) involved in the task. Bernstein (1967) proposed that the process of skill acquisition involved “mastering the redundant degrees of freedom”, as it has been shown that multiple solutions are often available to a single motor problem, where different degrees of freedom are recruited during the generation of the solution. As such, controlling a high number of degrees of freedom has remained at the center of the study of human motor behavior. Humans are able to rapidly produce movements that require the organization of an unimaginably high number of degrees of freedom if viewed over all levels of analysis of the system. Gaining insight into the seamless, almost automatic execution of highly practiced movements such as writing, walking, or running from a complex systems perspective holds the possibility of its extension into the field of system organization. This is especially since corporations are composed of living systems and should in general possess similar be able to demonstrate similar structuring and organization of its behaviors.

Although many approaches, both theoretical and empirical have been employed in the examination of the degrees of freedom problem, there has been relatively little consensus. Much of the difficulty in finding consensus has been due to the lack of explicit definitions of the level of analysis, whether the theories and experiments were concerned with only the most overt macroscopic behavior, or the subsystems driving the system, or possibly, even the elemental variables. Thus, the empirical drive within this paper will be to address the aforementioned three levels of analyses within the acquisition a whole body movement.

Constraints: Perspectives from Motor Behavior and System Organization

From a system organization perspective, Goldratt (1990) has proposed that the process of change required the generation of the simplest solutions to core problems, invented by the appropriate personnel, termed the Theory of Constraints. Within Goldratt's framework, learning can be seen as *change*, an adaptation that generates a solution to a given problem. A similar view of motor behavior can be taken, as every task to be performed can be seen as a problem posed to the motor system, which requires an optimized solution. Three key points of the Theory of Constraints in the affecting of change are:

1. Pinpointing the problem at hand
2. Selecting the appropriate personnel to create the solution
3. Generating the simplest possible solution to the problem

The first step of pinpointing the problem is analogous to a search of the perceptual-motor workspace (Newell & McDonald, 1994) as means of finding the appropriate goal states. Application of this Theory of Constraints to motor problems would result in a hypothesis that the simplest behaviors emerge with practice through the reduction of behavioral dimensions (Haken, 1996) while the behaviors of the individual body segments involved in the task are either recruited or suppressed (i.e., move or not move), depending on the context created by these constraints. The recruitment-suppression hypothesis (Buchanan & Kelso, 1999) suggests that the amplitude of motion of the individual body segments is increased in the supplementary planes of motion. Thus, an individual drawing a straight line with an increasingly curvilinear arm segment trajectory would considered as being representative of the "recruitment" more degrees of freedom, while the opposite would be characterized as the suppression of these degrees of freedom. Within the field of motor behavior, the confluence of task, environmental, and organismic constraints has been proposed as being responsible for the organization of the degrees of freedom that allow the emergence of human movement (Newell, 1996).

For an intentional system, its behavior is dependent on the goals of the task perceived by the actor, whose performance and strategies employed to achieve these goals are limited by its own physical capabilities, functioning within both stable and unstable environments. In this current study, two constraints play a role in the emergence of the motor solution. Firstly, the task requires adapting to the task apparatus, in which the most simple/stable solutions may limit the adaptability of the system. Secondly, individual differences would provide insight into the different strategies employed during the selection of solutions to the motor problem.

Destabilizing and Stabilizing Coordination Patterns

Based on the HKB (Haken, Kelso, & Bunz, 1985) model of human coordination, it is proposed that we possess two inherently stable patterns, namely, in-phase and anti-phase. The relative phase, or phase angle difference between two moving segments can be determined via its velocity and position (see Figure 1 for illustration of in-phase and anti-phase behavior).

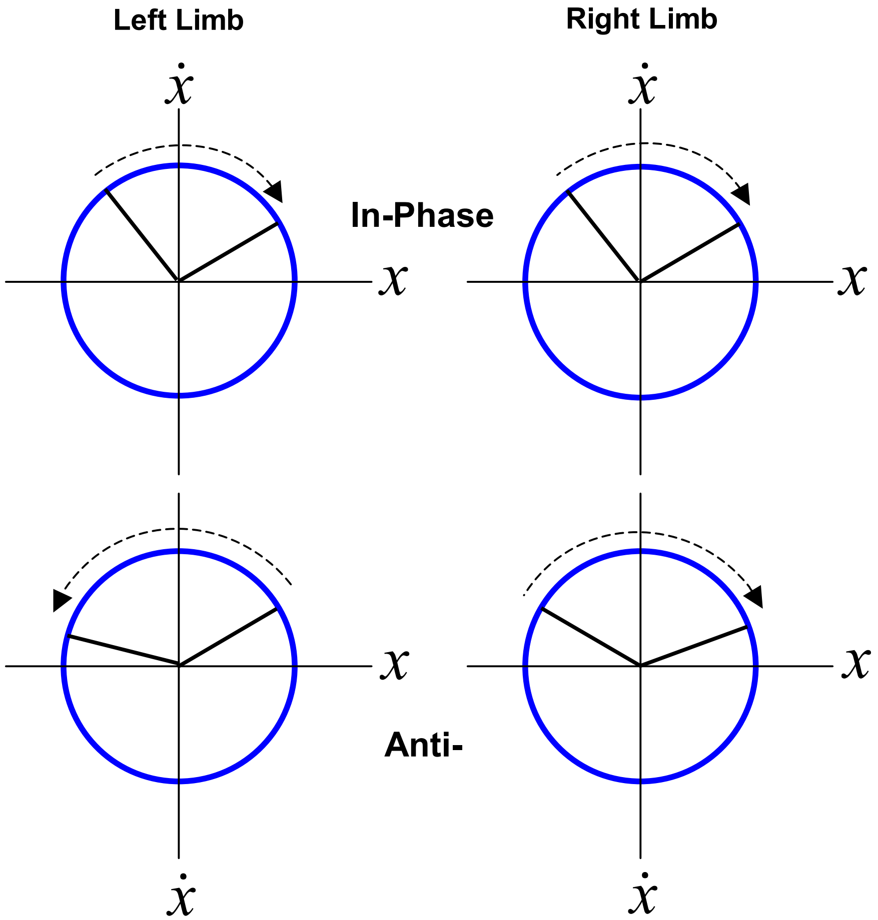

Figure 1. Visual representation of relative phase between the motions of two limbs. Both in-phase (above) and anti-phase (below) patterns are represented.

In the HKB model, the anti-phase pattern is an asymptotically stable fixed-point, whereby a phase transition is made from anti-phase to in-phase at a critical value of the control parameter, the oscillation frequency. As the movement speeds are increased, the limbs are no longer able to maintain the anti-phase pattern and an involuntary, unintentional shift to the in-phase pattern is made. During the acquisition of a novel coordination pattern, these inherently stable patterns must be destabilized to allow the new patterns to become stable (Zanone & Kelso, 1992, 1997), though Buchanan (2004) has shown that the destabilization of the inherent patterns may be limited to the coordination between two limbs. Two possibilities arise from these ideas. First, the ideas of Zanone and Kelso suggest that macroscopic stability is a commodity in short supply, and that a tradeoff must occur, with the inherently stable patterns sacrificed, maintaining the simplicity of the over behavior. Buchanan's findings however, suggest in contrary, that rather than sharing the stability, the system increases the complexity of its macroscopic behavior, by increasing the number of macroscopic stable states available to the system.

The current paper analyzes the reorganization of the microscopic components (segment motion in 3-dimensional Cartesian space) of the system that give rise to the macroscopic behaviors (center of mass motion) during the learning of a whole body movement task, through the use of Principal Component Analysis (PCA). As a measure of complexity or irregularity of the behavior or each individual component, we used Approximate Entropy (ApEn) as the analysis tool for the various time series.

Methods

The only instructions provided to the participants were that they were to learn to produce large amplitude sideways movements on the apparatus as fluently as possible. In order to increase the difficulty, the participants were required to perform these movements with arms held behind their backs (Vereijken, Bongaardt, Whiting, & Newell, 1992). Each participant completed 7 days of practice, with each practice day comprising 20 trials, each 30 s in length, with a rest period provided following 10 trials or at the subject's request. For this study we compare three practice blocks of 5 trials each. Block 1 comprised the first 5 trials on the first practice day while Block 2 comprised the last 5 trials on the same day. The last 5 trials on the last day of practice, Day 7 comprised Block 3.

The ski-simulator (Skier's Edge, Park City, Utah) is an apparatus that has been promoted commercially as a rehabilitation device and also being an approximation of the requirements of slalom skiing. This apparatus comprises two co-dependent foot plates on a wheeled platform, situated atop two parallel bow-shaped metal rails, harnessed to the rails by an elastic belt. Whenever forced away from the center of the apparatus, the elastic band returned the platform to its resting position. The bow-like shape of these rails required angular motion, as opposed to linear horizontal motion where a prior study has shown that much of the forcing is due to the torque produced by angular motion of the subject's center of mass (Vereijken et al., 1992).

A sampling frequency of 50 Hz was used during data recording with a 3-dimensional motion capture system (SELSPOT). Two infrared cameras detected the positions of infrared light-emitting diodes (LEDs) in 3-dimensional space. Positions of thirteen LEDs were recorded during each trial, two placed on the edges of the platform and the remainder on the subject's body (Figure 3).

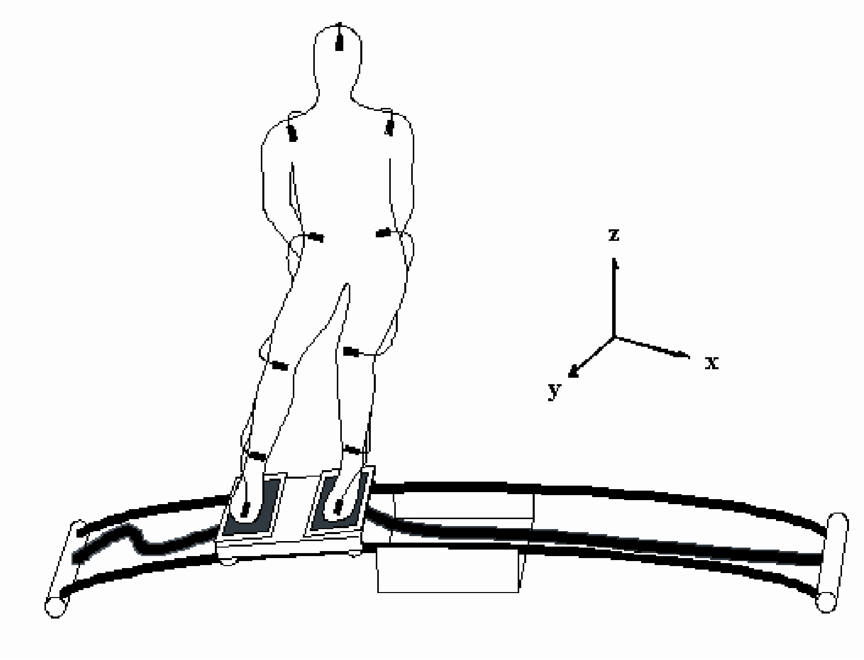

Figure 3. Schematic of the ski apparatus and experimental set-up. The three axes in Cartesian space are provided (X = medio-lateral, Y = anterior-posterior, Z = superior-inferior).

Positional data of the 13 LEDs collected over the course of a trial served as raw data. In order to remove the effects of learning on the manner in which participants initiated the trial, data from the first 5 s of each trial were discarded. From the raw data, the total body center of mass was determined using a segmental method using the regression equations from Chandler, Clauser, McConville, Reynolds, and Young (1975). As the positions of the upper and lower arms were fixed in relation to the body (arms held behind back), their respective contributions to the total mass of the body were combined with that of the trunk for these calculations. The positions of 6 body segments (head, torso, right and left thighs and shanks) in 3-dimensional Cartesian space provided the data for the Principal Component Analysis. The principal components were derived by obtaining the eigenvalues from the matrix of the correlation coefficients obtained from the original matrix of time series, while the eigenvectors provided the weightings, or relative contributions of each segmental variable within each component. Use of the correlation matrix as opposed to the covariance matrix negated the need for initial normalization of the data to unit variance (Kachigan, 1986).

The center of the platform was derived as the mean of the two points in space. The angle θ was calculated as the angle between the extrapolated axis of rotation for the apparatus and the normal on the frontal plane for the platform. For the center of mass, the frontal plane angle φ between its position and the perpendicular, with the center of the platform as the axis of rotation was calculated, while φ_2 was the sagittal plane angle for the center of mass calculated against the perpendicular (see Figure 4).

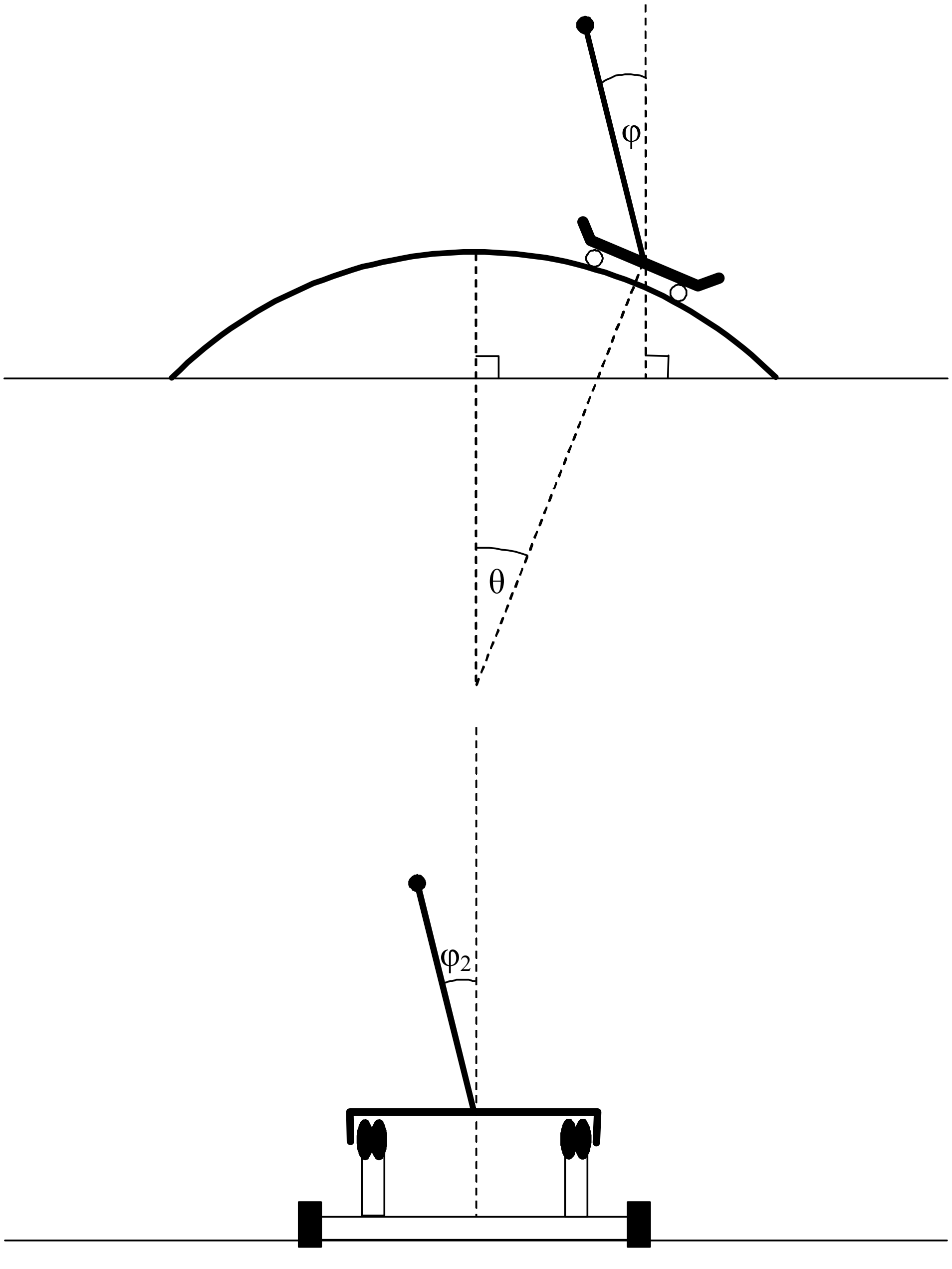

Figure 4. Diagrammatic representation of the derivation of angular positions of the platform and center of mass in both planes.

A multi-level model of the task can thus be generated, where the individual mechanical (joint level) degrees of freedom are considered the elemental variables which were involved in the subsystems that gave rise to the macroscopic behavior. A representation of this model can be seen in Figure 5.

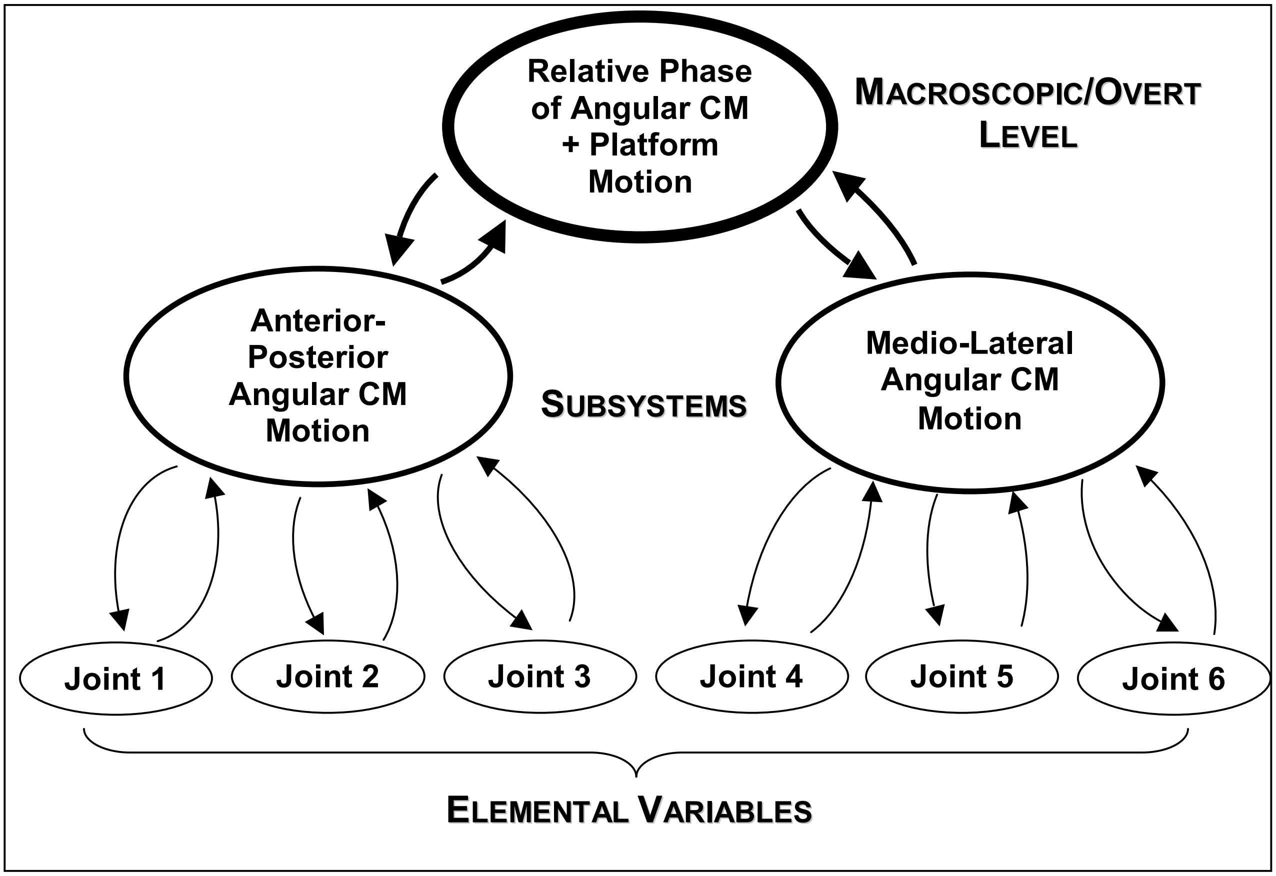

Figure 5. Illustration of the synergetic model, in which different elemental variables are recruited to support the various subsystems that generate and are generated by the macroscopic behavior.

Continuous relative phase between the medio-lateral motion (φ) and anterior-posterior (φ_2) of the CM was calculated using the normalized velocities and positions of the individual time series. The phase angle at any given point in time was derived from the arctangent of the velocity divided by the position. Relative phase was then calculated as the absolute difference in phase angles at a given point. The distributions of these values were obtained using histograms divided into bins ranging from 0^o to 360^o, with bin widths of 30^o. The bin with the highest occurrences was then represented as a percentage of the total time series. The stability of the relative phase pattern served as a measure of the macroscopic overt behavior.

ApEn (approximate entropy) served as a measure of signal complexity, a measure of regularity, where values near zero reflect highly periodic outputs. Increasing values of ApEn represent greater irregularity within the signal a marker of higher dimensional behavior. ApEn calculations were performed using the algorithm provided in Pincus (1991), seen below.

$$ApEn(\vec{X}, m, r) = \ln\left[\frac{C_m(r)}{C_{m+1}(r)}\right]$$

This analysis tests the recurrence of patterns of length m within the vector X within r of the standard deviation serving as the similarity criterion. The recurrence of patterns of length m is compared against patterns of length $m + 1$, providing a measure of relative prevalence of these patterns. What is obtained is the log likelihood of the ratio of recurrence of vectors of length m against vectors of length $m + 1$ within the range of r. In general, it is unlikely that a longer vector will repeat more often than a shorter one, thus the minimum ApEn value will be the natural logarithm of 1, which is 0. If the predictability of the time series were low, C_m will greatly exceed C_{m+1}. In a highly predictable, low dimensional time series, C_m and C_{m+1} are closer in magnitude and result in smaller ratios. Thus, smaller values describe a predictable time series, where similar patterns are more likely to follow one another, while a high ApEn value suggests a highly irregular time series, where the predictability of subsequent patterns is low. As per the recommendations of Pincus (1991), a value of 2 was set for *m*, while *r* was set at 0.2.

Results

Effect of Practice

With practice, the amplitude of the platform increased greatly with practice. In Figure 6, a clear increase in the motion of the platform within a given movement cycle can be noted. Overall, all participants improved their performance with practice.

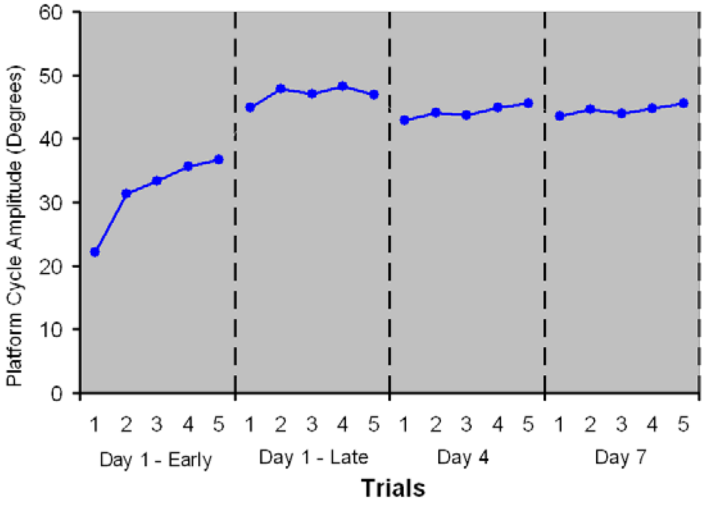

Figure 6. Average platform cycle amplitude over all the participants.

Principal Component Analysis

The primary finding from the PCA was that the number of components required to capture 90% or more of the variance did not reduce, remaining at 3 components (4 on rare occasions) from the beginning to end of practice. The most crucial finding of the study was found within the reorganization of the significant variables within the components (due to the length of the time series generating a high number of data points, a significant weighting was set at 0.25 per Kachigan, 1986). A consistent structure, which was absent in early practice was found during late practice, whereby a similar organization of significantly weighted variables within each component emerged with practice, across both participants and trials. The first component encompassed the medio-lateral axis variables for all the segments, while significant weightings were found for the anterior-posterior axis for the thighs and shanks (see Table 1 for a summary). In the second component, all the vertical, superior-inferior axis variables proved to be significant for all the variables, while motion of the head and torso on the anterior-posterior axis were significant for the third component, thus accounting for all the variables within the principal components analysis. This structure was used as a means of grouping the variables during the analysis of output complexity, where the average ApEn values of the significant variables within each component were obtained.

Table 1. Distribution of significant weightings within the 3 principal components (PC) during late practice (seen during late practice for all subjects).

Segment	Axis	PC1	PC2	PC3
Head	X	*		
	Y			*
	Z		*	
Torso	X	*		
	Y			*
	Z		*	
R Thigh	X	*		
	Y	*		
	Z		*	
L Thigh	X	*		
	Y	*		
	Z		*	
R Shank	X	*		
	Y	*		
	Z		*	
L Shank	X	*		
	Y	*		
	Z		*	

Note: * denotes significant weighting

Macroscopic and Microscopic Complexity

Overall, the variables within the first component decreased in complexity with practice, across all participants. Similar changes due to practice were also noted in the second component. Within the third component however, all but one participant increased in output complexity (Table 2).

Table 2. Average ApEn values of the relevant elemental variable time series within each principal component (PC).

	PC1			PC2			PC3		
	Block			Block			Block		
Participant	1	2	3	1	2	3	1	2	3
AV	0.359	0.351	0.325	0.479	0.445	0.425	0.294	0.263	0.350
BR	0.402	0.409	0.332	0.476	0.461	0.445	0.291	0.292	0.169
JT	0.369	0.329	0.310	0.557	0.402	0.420	0.219	0.228	0.280
MT	0.403	0.361	0.329	0.516	0.407	0.443	0.173	0.215	0.316
SN	0.384	0.321	0.321	0.493	0.492	0.435	0.260	0.293	0.360

In the primary plane of motion, the angular motion of the center of mass driving the platform decreased in complexity for all participants. Interestingly, participant BR demonstrated an increase in complexity from Block 2 to Block 3. The equilibrating anterior-posterior motion of the CM however, showed increasing complexity for all participants with the exception of one (Table 3). Participant BR decreased in complexity following an increase during Block 2.

Table 3. ApEn values within of the CM motion in the two planes.

	CM Medio-Lateral (ApEn)			CM Anterior-Posterior (ApEn)		
	Block			Block		
Participant	1	2	3	1	2	3
AV	0.340	0.301	0.244	0.436	0.422	0.534
BR	0.377	0.271	0.290	0.411	0.439	0.296
JT	0.288	0.295	0.257	0.470	0.454	0.404
MT	0.402	0.313	0.264	0.334	0.431	0.415
SN	0.369	0.311	0.245	0.421	0.404	0.491

The direction of change for the stability of the relative phase pattern was not universal, though an increase in stability was noted for 4 of the 5 participants, though the individual directions of change differed between them (Table 4). A marginal decrease was noted for one participant.

Table 4. Percentages of the total time series in the bin with the highest frequency counts as an index of stability of the macroscopic behavior.

	% of Time Series		
	Block		
Participant	1	2	3
AV	14.7%	13.9%	19.9%
BR	13.8%	17.7%	14.9%
JT	12.8%	18.2%	29.9%
MT	14.7%	14.2%	13.6%
SN	14.1%	16.4%	15.8%

Discussion

Reorganization of the body segments occurred with practice, though the increased stability of the macroscopic behavior was marginal, the grouping of significant weightings of the dependent variables within each of the principal components, despite a lack of change in the number of principal components required to capture a significant amount of the variance within a trial. This suggests that three sub-tasks were required to achieve the overall macroscopic task goal, maintaining a fluid motion of the platform with maximal amplitude. Principal component 1 represented the platform forcing motion (torque) generated by the body, primarily the medio-lateral motion of the torso, head, thighs and shanks, but also encompassing the forward and rearward motion of the lower limb segments as well. Principal component 2 comprised the vertical motion of all the segments, involved in maintaining the downward vertical force, while the final component encompassed the anterior-posterior motions of the torso and head, creating an anterior-posterior torque to counter the forward motion resulting from knee and ankle flexion (Figure 7). Such restructuring is analogous to the selection of the appropriate personnel within the Theory of Constraints, where the body segments were reorganized to achieve the different goals for each sub-task, as the lower limbs were used to drive the platform, while the upper body segments were used to counter the forward motion of the lower limbs during the forcing of the platform.

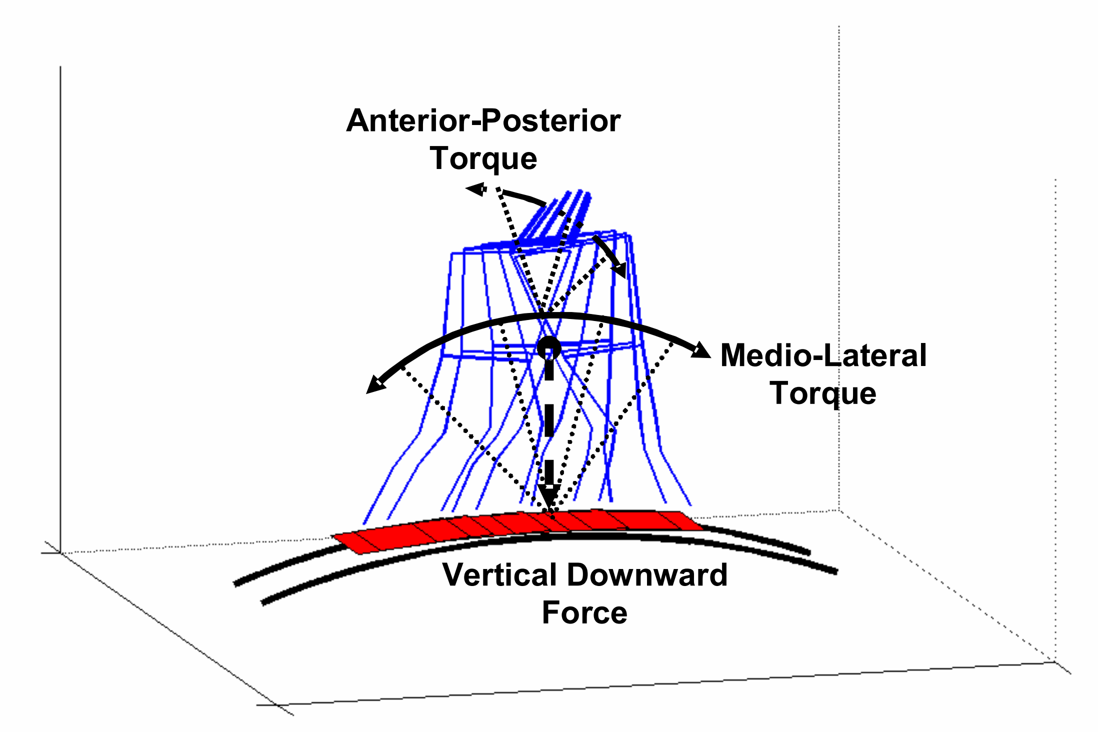

Figure 7. Schematic 3-dimensional view of a participant's movements during a single movement cycle on the ski-simulator. The 3 key components of the movement are illustrated.

With practice, stabilization of the first two components is compensated for with increasing complexity in the anterior-posterior motion of the torso and head for all but one participant. At the subsystem level, this is reflected in the changes in complexity of the angular motion of the center of mass where the forcing (medio-lateral) motion is stabilized while the equilibrating (anterior-posterior) motion becomes increasingly complex, with the complexity of the output dependent on the sub-task requirements. These changes occur in a synergetic, complementary fashion where an increase in complexity of the motion in one plane is mirrored by a decrease in another, supporting the idea that the stability of the macroscopic behavior is a limiting factor and requires compensatory changes at subsystem and elemental levels.

The medio-lateral, sideways motion of the CM satisfied Goldratt's (1990) proposed solution simplicity, as the complexity of its motion decreased with practice. Thus, the subsystem that has to interact with the apparatus or environment generates an increasingly simple output. However, the anterior-posterior angular motion of the CM is more likely to better serve the system by functioning with increased complexity, which allows for a more efficient maintenance of upright posture that is more reflexive to nonlinearities or stochastic properties of the environment. For the forcing, task related motion, a more simple output is beneficial, as it allows for a more fluid, rhythmic motion of the platform. The increasingly complex postural output can be seen as the "absorption" of the variability that may arise from the forcing motion and the elastic belt, allowing the driving of the platform to become increasingly regular. With the consideration of sub-task requirements, suggesting that task constraints are effective at the subsystem level. Complex behaviors may thus be beneficial for a certain subsystem, while greater simplicity may be beneficial for another, as long as they function in a synergetic fashion through cooperation and competition, preserving the macroscopic behavior (Haken, 1983), but with respect to the requirements of the sub-task. In parallel to Goldratt (1990), such synergies could be seen as a compromise being struck between the subsystems, allowing for increasingly simpler macroscopic solutions to emerge.

The findings of this study show that increases in performance can be achieved with only a marginal change of the stability of the macroscopic behavior, but through complete reorganization of the personnel that work to generate this global output, if one views each limb segment being viewed as an employee with a different set of skills/abilities. The most overt behavior or the overall solution to the motor problem, marked by the stability of the relative phase remains relatively unchanged over the course of practice. Such stability at the macroscopic level was maintained despite the numerous changes at the elemental and subsystem level. This highlights the benefits of redundancy within the system, which allows complete reorganization of the behavior, but no resultant instability. Having redundant personnel in an organization can provide a great benefit, which allows multiple personnel members to perform similar functions, while maintaining their ability to perform different ones as well. This allows personnel to be recruited by different subsystems, when the need arises. From an organizational perspective, altering their outputs to satisfy problems at the subsystem level cannot be performed independently of the other subsystems. Such a statement can be made as the current study has shown that the subsystem that deals with environmental demands simplifies its output, while being supported by the other subsystem.

Overall, we have shown that the process of learning motor skills holds similarities to the process of change proposed by Goldratt (1990). This current study has shown that the motor system however, is able to reorganized and change its output without destabilizing its behavior at the macroscopic level. The motor system is able to maintain its macroscopic stability through the recruitment and suppression of the redundant degrees of freedom that it possesses. Such similarities between motor learning and organizational theories hold much promise for the future, as the understanding of the human organism can be extended to other goal-directed systems, allowing them to function as smoothly as the seemingly seamless execution and organization of human movements.

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