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A Dynamic Systems/Constraints Approach to Rehabilitation

Uma abordagem dos sistemas dinâmicos/Restrições para a reabilitação

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Abstract

Background: Classification systems (Nagi, International Classification for Function [ICF]) have become popular for categorizing the level of ability (ICF) or disability (Nagi) associated with movement disorders. Nevertheless, these classifications do not explore the ways in which one level may influence other levels. For example, how might the weakness and stiffness associated with some cases of cerebral palsy result in a stereotypical toe-gait? In this overview we describe a dynamic systems/constraints (DS/C) approach to understand relationships between levels, and how the approach can be used to rationalize a novel process for the evaluation and treatment of movement disorders. Objectives: There are three specific aims in this paper: first to present a general systems approach to understanding behavior at different levels; second to present tools of, and the results of empirical work using the DS/C approach; third to discuss the clinical implications and results of clinical interventions motivated by DS/C analysis for children with cerebral palsy, and individuals with Parkinson disease.

Key words: Nagi; ICF classification systems; dynamic systems; biomechanics; coordination dynamics; dynamic resources.

Resumo

Contextualização: Sistemas de classificação (Nagi e Classificação International de Funcionalidade (CIF)) têm se tornado populares para categorização do nível de habilidade (CIF) ou de incapacidade (Nagi) associado com distúrbios do movimento. No entanto, essas classificações não exploram as formas pelas quais um nível pode influenciar outros níveis; por exemplo, como a fraqueza e a rigidez observadas em alguns casos de paralisia cerebral podem resultar no padrão estereotipado de marcha equina. Neste artigo, descreve-se uma abordagem denominada sistemas dinâmicos/restrições (DS/C) para compreender as relações entre níveis e como ela pode ser utilizada para racionalizar um novo processo que norteie a avaliação e a intervenção de distúrbios do movimento. Objetivos: Este artigo tem três objetivos específicos: apresentar uma abordagem geral sistêmica para compreender o comportamento em diferentes níveis de análise; apresentar ferramentas e resultados de estudos empíricos que utilizaram a abordagem DS/C e, por fim, discutir as implicações clínicas e os resultados de intervenções motivadas pela análise DS/C voltadas para crianças com paralisia cerebral e indivíduos com Doença de Parkinson.

Palavras-chave: Sistemas de classificação Nagi; CIF; sistemas dinâmicos; biomecânica; dinâmica da coordenação; recursos dinâmicos.

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Introduction

The main goal of physical therapy is to assess and treat movement disorders that result from injury and that are typically exacerbated by pain. In the United States the profession of PT, under the mandate of the American Physical Therapy Association, has resolved to incorporate, and support the development of, evidence-based and theory-based clinical procedures in evaluation, diagnosis and treatment (e.g. see: Proceedings of the III-Step Conference (2005) "Translating Evidence into Practice"). At the same time, the challenge to better grasp the underlying mechanisms behind movement disorders has also been recognized by the broader rehabilitation and scientific community. As early as 1996 a consensus of presenters at a gait meeting sponsored by the National Center for Medical and Rehabilitation Research (NCMRR)[1] made a strong call for a better theoretical understanding of the causes underlying abnormal locomotor patterns, through, for example, muscle modeling[2] and kinetic analysis[3]. This sentiment was reinforced in the II-Step Conference. Nevertheless, locomotor models that can be used to better understand the relationships among neural pathologies, impairments and the resulting movement patterns tend still to be the exception in the literature. The purpose of this paper is to present a dynamic systems/constraints theory and to describe models grounded in this theory as a means of guiding our modes of reasoning on the relationships between different descriptive levels of injury, particularly between the levels of impairment and function. The perspective that we present will be used to rationalize departures from traditional methods of evaluation and intervention in children with cerebral palsy and in individuals with Parkinson's Disease.

Classification systems

A useful starting point for the investigation of the relationships between impairment and function is to categorize the level of ability or disability associated with a given movement disorder. In recent years, there have been a number of categorization systems devised and their merits debated in the literature, some focusing on what the patient cannot do (the disablement model of Nagi[4]), and some focusing on what the patient can do (the 'enablement' models of the World Health Organization, International Classification for Function - ICF). The detailed pros and cons of this debate are outside the scope of the present paper. Nevertheless, we posit that the modeling approach described below lends itself to a more insightful understanding of the relationships between *impairment* and *functional limitation* (Nagi classification system) or, similarly, between *body functions and structure* and *activity* (the ICF classification system, Figure 1). The problem with both categorization systems, however, is that while they describe the *level* at

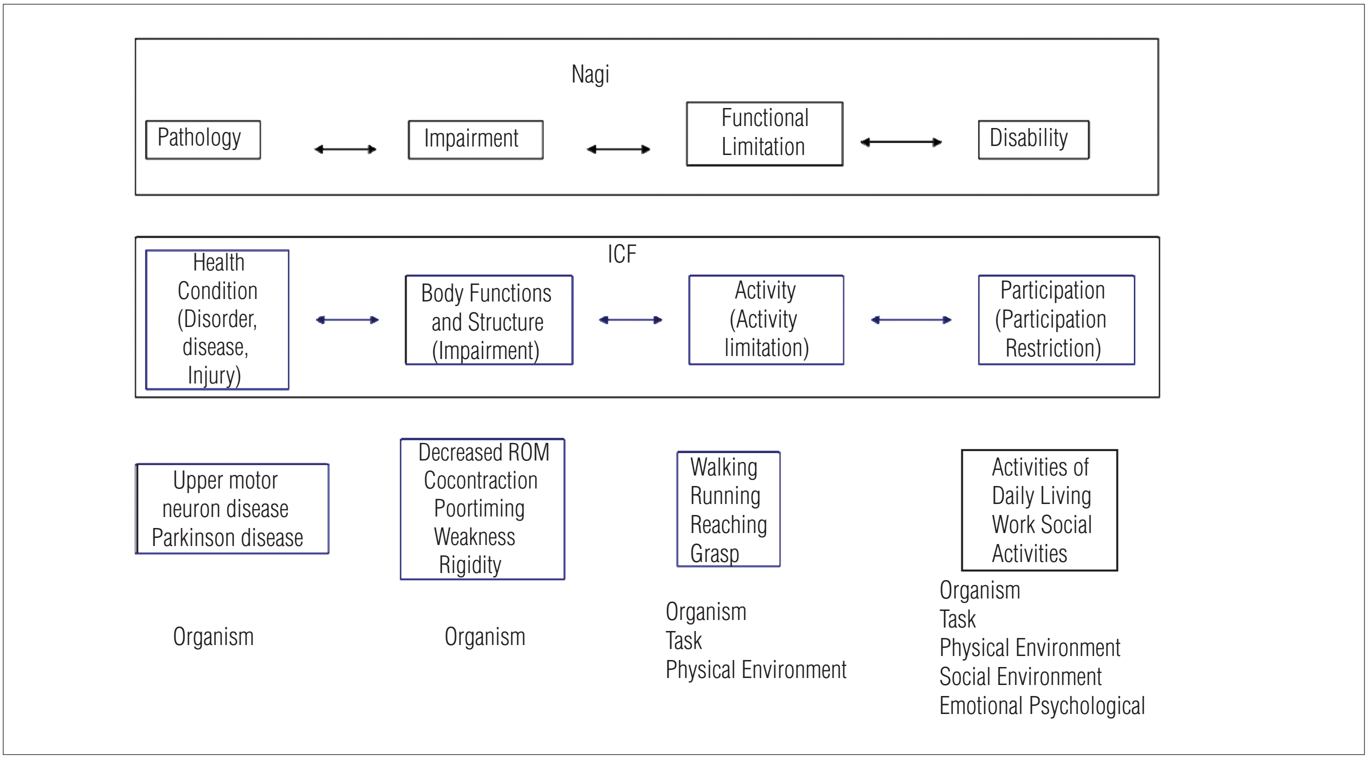

Figure 1. The Nagi and ICF classification system with examples. From a dynamic systems perspective different levels of classification include more or fewer constraints and from different sources in the emergence of preferred motor patterns. Nagi and ICF classifications use similar concepts and terminology but the ICF reflects a more positive bias (for example ICF uses activity limitation vs functional limitation, participation vs disability).

which the patient's problems lie, they fail to provide an understanding of the *relationship between levels*. For example, how does the limited strength and timing of muscle contractions of children with spastic cerebral palsy result in a stereotypical pattern of equinus or toe gait? The answer to this type of question requires a precise description of the relationships between impairments and activity/functional limitations. More generally, a rigorous understanding of these relationships in movement disorders can lead to better diagnoses and the design of more efficacious treatments for such disorders.

Dynamic systems

The fundamental premise of dynamic systems theory when applied to coordination and control is that movement patterns *emerge* from the interplay of the constraints between and within the elements of the system. A *dynamic* system is composed of multiple interacting components (atoms, cells, organs, individuals, etc...). Over the life span, individuals grow, become strong, develop perceptual and motor skills, lose muscle and bone strength, lose acuity of the senses, and as a result movement patterns change. We suffer injuries to the neuromusculoskeletal systems may produce long-term changes in the ways we move. The tasks we must perform change as we mature and become parents and workers, and then retire. The environmental milieu is in a constant state of flux. The patterns that emerge are a reflection of these changing organismic, task and environmental constraints. From a developmental perspective the research of Thelen[5] and colleagues provides many nice examples of how movement patterns emerge and disappear as a function of changing constraints (e.g. leg strength as a proportion of body weight) in the individual as they relate to the gravitational environment (see also Savelsbergh[6]).

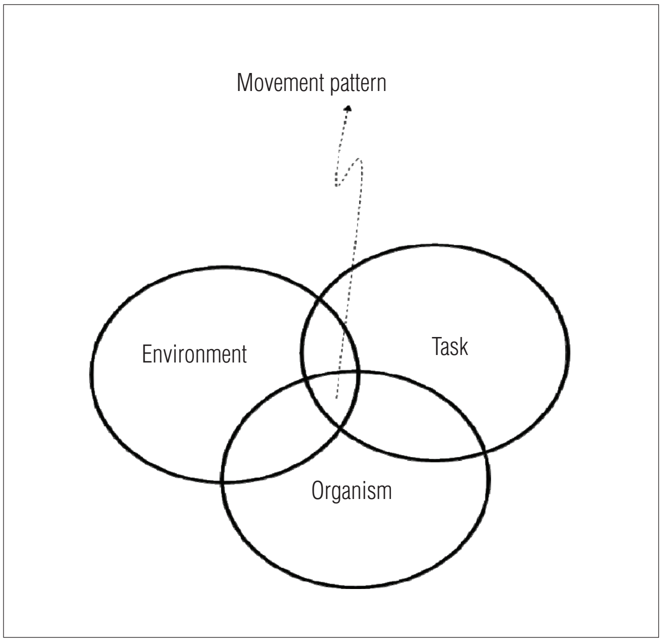

Figure 2. Venn diagram illustrating the interrelationships of organism, task and environment. In a systems approach the emergent pattern arises from the interplay of constraints, and skilled actions are not dictated by the organism. By expressing constraints across the elements in terms of required forces and torques, the expressed patterns can be understood in biomechanically lawful ways.

Thus, the system is dynamic in the sense that all of the constraints and their concomitant interactions change in time as do the consequent emergent patterns of movement. Newell[7] introduced a conceptual framework to outline the types of constraints that either restrict or support the occurrence of certain movement patterns. As in Newell's approach, the conceptual model we have adopted has three elements involving constraints that arise by nature of the task, the organism and the environment (Figure 2). In this article we have limited the application of Newell's model to the interaction of forces between organism and environment embedded in task dynamics. Tasks require forces for their completion. The organism can generate forces and conserve forces through its own properties and in its interactions with the environment.

There are other important constraints influencing the appearance and time course of the movement forms that occur at the psychosocial level - motivation, arousal and perception for example (Figure 3). The relations between constraints at this 'psychological' level will require significant insights and future research, because the variables are not easily translated into the mechanical 'language' of movement production (forces, torques, etc...). Nevertheless, significant advances have been made through an ecological approach that seeks to understand the manner in which objects, events and surfaces in the environment are perceived as affordances, i.e. in relation to their ability to specify and guide actions. Affordances are mapped to the corresponding abilities (effectivities) of the organism through circular feedback process of environment-organism coupling (for example[8-10]). Action selection, for example, can be conceived as resulting from the interaction of task, organismic, and environmental constraints that act at the psychological level, i.e. at the intersection of the set of effectivities in the organism's behavioral repertoire (task constraints), the currently perceived set of affordances (environmental constraints) and the personality, life history, and current motivational state of the organism (organismic constraints). However, the interplay of the physical and psychological aspects of movement still requires significant investigation. For example, how does the perception of affordances influence the unfolding interactions of forces and torques in the physical domain in the task, organism and environment domain, and how do the resultant interactions influence the perception of affordances?

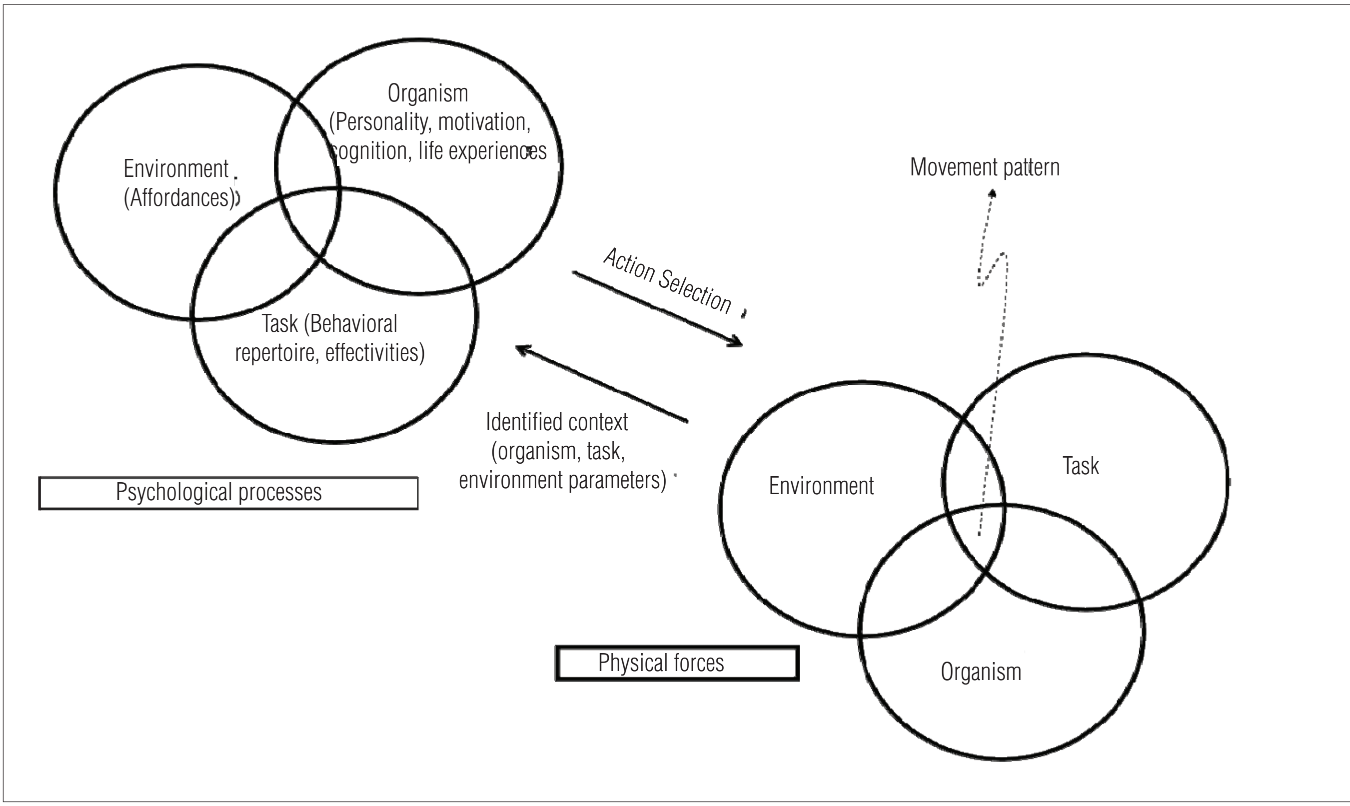

Figure 3. One possible way to think about the influence of constraints that do not translate easily into forces and torques is to build a separate system that involves psychological processes. The physical and psychological domains interact such that tasks to be done and their movement patterns emerge.

For the purposes of this paper we focus primarily on the system behaviors in the physical domain. As organismic constraints change over time (some slowly during development and in slowly progressing diseases, and some quickly as might occur following injury in a motor vehicle accident) the emergent behaviors change correspondingly. In this sense the 'control' of movement and its patterns is distributed across the array of constraints (see Special Issue, Human Movement Science, 1996), in stark contrast to traditional top-down ('brain-driven') models of control that for many years had been the theoretical underpinning for evaluating and treating neurological disorders, and in some cases (for example, neurodevelopmental approaches -NDT) continue to do so.

The examples in this paper are largely limited to disorders of locomotion, a critical functional activity. Activity limitations in walking in patients with neurological disorders (e.g., children with cerebral palsy, individuals with Parkinson Disease - PD, or individuals suffering from a stroke) may result in loss of mobility. In some cases the loss of mobility results in profound disabilities related to cognitive social and survival functions, feelings and loss of independence and social acceptance[11-13]. Loss of mobility may even result in further pathophysiologies such as decreased cardiac function, musculoskeletal disorders and other long-term medical complications associated with the chronic use of assistive devices such as wheelchairs and crutches[14]. Apart from its practical significance, locomotion is a highly skilled, complex behavior that entails 'local' rhythms at the muscle joint and segment levels and lends itself well to the dynamic systems approach, which has been applied with much success to rhythmic skilled movements in general[15]. At a more global functional level, locomotion also entails translation of an end-effector (the body's center of mass) along a desired path and/or to a specific goal, and lends itself to the investigation of the dynamics of navigation through a structured environment.

A dynamical account of body structure (impairments) and activities

One key to understanding the relationship between the constraints/dynamics approach and the Nagi/ICF models is the recognition that as the analysis moves from the pathology to participation, the systems approach requires that we consider an increasing number of elements accompanied by constraints and their interplay that are likely to influence the emergence of a particular movement pattern (Figure 1). For example, the body structure level focuses primarily on the disordered function of subsystems (e.g., organs, muscles, and extremities) of the organism. Decreased muscle strength, decreased range of motion, poorly controlled muscle contractions, and decreased cardiac function are examples of relevant variables. At the activity (functional) level, however, coordinated movement patterns emerge that are not only due to constraints imposed by the mechanics of body parts, but also by the task requirements and environmental constraints. For example, assume the task is to catch a bus that has stopped across a busy street. The task requires a certain function, locomotion, to be successfully completed. The movement form that is adopted to achieve the locomotion (e.g., walk, run, or wait for the next bus) will be influenced by the action capabilities of the individual (effectivities), by task parameters (imminent bus departure) and environmental factors (icy roads, obstacles, and traffic).

A perceived imminent bus departure might require running, but knee pain may cause the individual to adopt a gait pattern that might look like a running limp. The fact that there is traffic in the road may cause an interrupted gait pattern. While this may seem intuitively obvious, it is not evident in the description of disablement/enablement models where locomotor functions had been described as 'whole body' movements[16], seemingly ignoring the influence of tasks and environments. In the dynamic systems approach a function (e.g. locomotion) would be defined as a family of movement pattern or forms (e.g. walk, run, crawl, tarzan-like brachiation between overhanging branches of a tree) that share certain goals in common (translate along a given path, e.g., a circular running track or from point a to b). The form that emerges is constrained not only by the organism, but also by the types of task to be performed and the physical environments in which they are performed. At the participation level, consideration of the psychological organism (for example, with motivations and drive), and the social environment (for example, support systems) will also influence the form of the emergent patterns.

The constraints-dynamics approach highlights the relationships among the different levels of the enablement model. To fully understand how particular movement patterns emerge we must develop models that capture in lawful ways the interplay of constraints within the task-organism-environment synergy. Further if we wish to understand how damage to body structures (impairments) result in changes in movement form and function, we must have a good understanding of precisely how organismic constraints interact with task and environment to shape the emergent movement pattern.

Similarly, sudden parametric change introduced to an ongoing task e.g. one that requires an individual to locomote at higher speeds will result in a change of the movement pattern. Dynamic models have been applied to the changes in such patterns across the transition from a walk to a run[17]. Additionally, transitions from a slow walk to a faster walk pattern in which the coordination of the arm and leg motions, and coordination of the thorax and pelvis change have been investigated using similar methods (e.g.[18]).

Two tools for understanding dynamic systems and constraints.

1) Coordination dynamics

In the examples above, the tools of non-linear (coordination) dynamics have been used to describe, and predict changes in patterns defined by two or more concurrently oscillating body segments (such as arms and legs in walking)[15,19]. For many rhythmic movement patterns the laws of nonlinear coupled oscillators act as constraints in that if the behavior shows certain characteristics such as instability, there will be a required change in the coordination pattern to help stabilize the system[20]. Oscillators with different frequency characteristics will coordinate in predictable ways using these laws[15]. Coordination patterns change as a function of disease. For example, if a limb becomes stiffer through some change in neurological control and/or morphology, the fundamental frequencies of the two limb oscillators will be different and their coordination patterns should change in a lawful way. Thus, patients with neurological disorders show a different pattern of interlimb coordination than their non-disabled peers[21,22]. Individuals with Parkinson's disease often have hyperstable coordination patterns, coinciding with a reduced ability to switch between coordination patterns[23,24]. This finding suggests that stability of coordination patterns is an important constraint in complex movement patterns, and that coordination laws may help us understand (and treat) movement disorders.

The tool is extremely powerful, but also limited in the sense that the fundamental unit of measurement, the relative phase between limb segments is a kinematic description – it uses positions and velocities to assess coordination. In physical therapy we are evaluating and treating individuals with pathologies that essentially change their kinetics; the ability to produce enough force at the appropriate state of the system, increased or decrease stiffness that will influence their capability of storing and returning energy and so on.

While the laws governing coordination apply to all individuals, the resultant movement patterns differ due to anatomic, physiologic or other constraints that are just as relevant to the movement outcome. It is our contention that at least two dynamical constraints based in mechanics must be considered to fully understand the emergence of a particular movement pattern. The first factor to be considered is that preferred emergent patterns are a direct reflection of the most effective use of the *dynamic resources* that are available to the individual (Figure 4). Dynamic resources refer to properties of the neuromusculoskeletal system that are available to the individual, and can be used generate and conserve forces for performance of a task. Active resources provide accurately timed concentric muscular contraction to generate force. Passive resources can be combined in ways that provide the ability to use body segments in a pendular fashion, and the soft tissues to act as springs that can conserve energy. Of course, pendulums will function only in a gravitational field, highlighting the second factor that must be considered for understanding a movement pattern's emergence, namely, the interplay of environmental and organismic constraints. The focus of the next section is on the constraints arising from the effective and efficient use of dynamic resources and from anatomical constraints that are 'built into' the musculoskeletal system.

2) Biomechanical models and optimization

The performance of any task requires that body parts be provided with energy for work at the appropriate time and in the appropriate amount. During sustained rhythmic motion, forces are generated by muscles at the appropriate time to offset losses due to friction or braking, and mechanical energy is conserved trading off kinetic and potential energy (muscle/tendon elastic potential energy and gravitational potential) between different body parts (e.g.[25,26]). These sources and sinks of energy can be considered dynamic resources since they are available, in varying amounts, to the organism (Figure 4). Dynamic resources are useful to the individual only if they can be garnered at the right time and in the right amount. In brand new walkers, for example, the cumbersome, wobbly gait with little forward progression is replaced by a more normal gait pattern that is enabled by the discovery that the lower limbs can act as pendulums and springs that store and exchange PE and KE, and that appropriately timed contraction of the gastrocnemius-soleus muscle will provide the escapement for sustaining rhythmic motion[27]. Thus, if there is a neurological constraint that disrupts the normal timing of muscle contractions, no amount of strength will benefit the child because muscle forces cannot be produced at the right time. Conversely, normal timing of muscle contractions will be ineffectual if there is insufficient strength to meet task (and thus environmental) demands.

In modeling gait, we must take into account changing dynamic resources of the organism within the current task and environmental context. Within the boundaries set by anatomical and other organismic and systems (task and environmental) constraints there are still many ways that the body can move. Typically developing young children have the dynamic resources to walk and run, but they can also jump, hop, skip, bound, creep, crawl, and walk on all four limbs to get around. They appear to be exploring a number of locomotor patterns. As adults, however, we usually restrict our locomotor patterns to walking or running, even although the alternative locomotor patterns are still available (e.g. Wagenaar and van Emmerik[28]). Even within a gait type, there are recognizable preferred patterns used between individuals. It is easy to recognize as different an individual who uses a 'silly walk' (Monty Python, episode 14 http://www.youtube.com/watch?v=oYlzTdSZeI4), or imitates Groucho Marx (http://www.youtube.com/watch?v=wD1SCL3nhdc).

In modeling locomotion, we also recognize that mature preferred movement patterns are optimal in the sense that they minimize particular set of cost functions e.g. metabolic cost, the likelihood of injury to tissues, and/or time taken to reach a goal location. To be optimal to the individual, a movement pattern must be adopted that not only takes advantage of the organismic resources, but also capitalizes on any resource that the environment has to offer. For example, gravity, ground reaction forces, and musculoskeletal geometry and anatomy provide a context for the conservative exchanges of PE and KE by allowing the legs and arms to be pendula during swing, and

Dinamic Resources (DRs)	Purpose	Contribution of Anatomy/Physiology
Spring	Store Elastic Potencial Energy	Passive (Soft Tissues: tendons, Ligaments) & Active (eccentric/isometric muscles)
Mass & Length	Store Gravitational Potential Energy (in a pendulum-like fashion)	Passive (Body Segments; tissues/viscera)
Mass, Moment of Inertia	Store Kinetic Energy (in a pendulum-like fashion)	Passive (Body Segments; tissues/viscera)
Dampig/ Braking	Lose/ Dissipate Energy (Absorb Shock)	Passive (Soft Tissues) & Active (eccentric/isometric muscle contraction)
Escapement/ Forcing	Gain Energy	Active (concentric muscle contraction)
Battery	Supply Energy	Cardiopulmonary System

Figure 4. Dynamic Resources. Fundamental methods for generating and conserving energy in a dissipative system. Resources may be used in different combinations and proportions for each 'special purpose' device (for example, running, jumping, throwing).

for the legs, inverted pendula during stance. That same context allows for the soft tissues to be used in construction of vertical springs during running[25] and hopping[29]. Bernstein[30] stated this premise quite boldly: "The secret of coordination lies not in wasting superfluous force in extinguishing reactive phenomena but, on the contrary, in employing the latter in such a way as to employ active muscle forces only in the capacity of complementary forces. In this case the same movement (in the final analysis) demands less expenditure of active force"[30]. It is our claim that adopted movement patterns are those that have been discovered and that evolve during development to best utilize the dynamic resources that are available to the individual in an environmental context.

One way to measure the effectiveness of dynamic resource utilization in tasks that have a high metabolic cost is to measure the cost of performing a task across a variety of movement patterns. For example, walking at a specific speed can be done using a long stride and low cadence (frequency), or by using a short stride length and high cadence (speed of walking = stride length*cadence). By using a metronome to specify cadence, it is possible to produce a number of combinations of stride length and cadence that will satisfy a particular speed requirement. Our research has shown that for any particular speed, an individual selects a stride length and cadence that requires a minimal amount of oxygen consumption and head stability. When driven away from the preferred combination, oxygen costs rise, and head stability is decreased (Figure 5). Similarly, our research has shown a direct connection between the body's kinetic energy (available through muscle forces and from energy conservation) and the associated metabolic cost, in relation to triggering transitions from walking to running in healthy individuals[31]. We have defined optimization to mean effective and efficient dynamic resource utilization within a certain movement pattern. It is our claim that when dynamic resources change (for example by a limitation of force generating capability because of an impairment) the system will reorganize and adapt its movement pattern to produce or conserve energy differently to achieve the same task goal in a way that is optimal; the movement pattern may look different, but the task is still completed successfully.

Anatomical Constraints on preferred movement patterns

It cannot be overemphasized that movement patterns for a given task are shaped to a great extent by simple anatomical constraints in relation to the interaction with the environment. In a typical walking pattern, the foot hits the ground in a slightly supinated position due to its structure, and the structures of

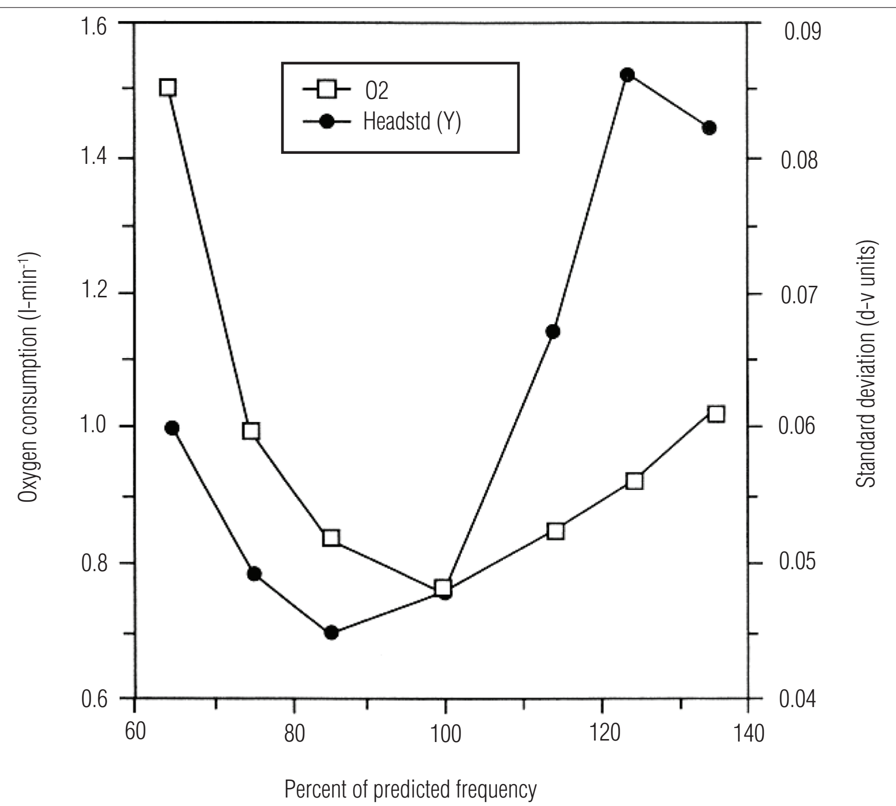

Figure 5. Quadratic curves for oxygen consumption (closed circles), and head stability (open squares) show a minimum cost at the walking frequency predicted by the resonance of a force-driven harmonic oscillator. Predicted frequencies matched preferred frequencies within one percent.

the surrounding tissues. Constraints due to bony and soft tissue connections and contact of the foot with the ground bring about a series of events that influence how segments and joints coordinate. Initial contact of the foot with the ground brings about a pronation torque on the foot, that in turn through the anatomy of the foot and ankle, causes the tibia to internally rotate[32]. Internal tibial rotation influences motion at the knee to help unlock the knee from its extended position, and allow for knee flexion to occur. At the same time the ground reaction force produces a flexor moment at the knee also causing internal tibial rotation and facilitating foot pronation. Thus, when the foot hits ground the movement pattern shaped by the organism-environment interaction would include pronation of the foot and knee flexion. As the body center of mass moves toward and then in front of the metatarsal heads it produces a moment around them, that allows the axis of rotation to move from the ankle to the metatarsophalangeal (MTP) joint axis. Subsequent release of the foot from it's fixed position on the ground, allow the passive stretch and active contraction on the G-S, to plantar flex the ankle, and by virtue of its line of action medial to the subtalar joint G-S will produce inversion of the calcaneus and supination of the foot. The bony articulation through the tibia at the knee also facilitates knee extension.

There are two points to be made with respect to this example. First, there is a certain architecture or structure that has a significant influence on the types of patterns that can occur. Second, we cannot understand patterns of functional activities unless we also understand how anatomical constraints relate to the environmental constraints (in this case the effect of the environment on the foot, and the rest of the body). Biomechanics is a tool that can be used to formalize the relationships.

To summarize so far: our overall goal in this paper is to first understand how impairments in body structure and function result in activity limitations (or more appropriately how impairments in body structure and function lead to functional *adaptations*). Impairments relate to the local malfunctioning of body parts, while activity limitations involve the global organism-environment synergy during task performance. We have taken the stance that activities cannot be understood simply as whole body movements isolated from the environment. The constraints approach focuses on the individual organism with its shared and unique dynamic resources, and the environments in which tasks are performed to determine the types of movement patterns that emerge. Impairments are but one category of constraints that influence function, and they can be thought of as changing the number and contribution of dynamic resources available to an individual in order to perform a task. A complete understanding of emergent patterns requires that we consider: control and coordination laws, mechanics as they relate to the availability of dynamic resources, and anatomical and environmental constraints in the performance of tasks.

In the remainder of this paper we will i) present a gait model that captures the interaction and flexibility of relevant task, environment and organismic constraints (vis-à-vis dynamic resources) in locomotion and allows us to make specific predictions with respect to the relations between impairments and functional limitations, ii) show how a further understanding of the dynamics of interlimb and trunk coordination in walking enables us to classify different disorder in the coordination of walking, and iii) show how this understanding can lead to specific changes in our physical therapy evaluation and treatment. We will use the results of a number of studies conducted on neurologically disabled individuals to illustrate the approach.

Dynamics of hemiplegic movement patterns in children with spastic hemiplegic cerebral palsy

Cerebral palsy (CP) is the most common pediatric neurological disorder in the United States affecting between 2 and 5 children per thousand births[33]. The cost of care for individuals with CP is estimated at about $8.2b for 2002 in the USA alone[34]. The number of children who suffer from cerebral palsy has shown rather large increases[35] as the percentage of very low birth weight (VLBW) babies (weighing 1500gm or less), a highly significant risk factor for the development of CP[36], has increased by 32% between 1990 and 2004[37].

At the impairment level some children with spastic cerebral palsy are characterized by inability to produce a sufficient amount of propulsive force at the right time in the gait cycle during the push-off phase of gait due to weakness and poor timing of muscle contractions in the gastroc-soleus muscle group[38]. Increased cocontraction of antagonist pairs[39,40], increases in spasticity as measured by passive tests, and hypertonicity are also characteristic of the neuromuscular impairments associated with some forms of CP. Studies have shown that increased resistance to joint displacement is more related to changes in the mechanical properties of the muscle-tendon passive components than to the presence of an altered stretch reflex[38,41-44]. Longer tendons and shorter muscle bellies may lead to increased resistance to passive stretch[45,46].

There are a number of non-typical features in kinematic gait patterns of children with cerebral palsy, e.g. decreased speed and stride length, and increased stride frequency[47,48]. Increases in walking speed in children with a diplegic gait pattern are achieved largely by increases in stride frequency[49]. A plantar flexed foot on initial ground contact[48], and decreased excursion of the hip and knee[49] are characteristic patterns of some individuals with cerebral palsy. A running-like gait pattern, with poor pendular energy exchanges between gravitational potential and kinetic energy[3], in-phase flexion of the hip, knee, and ankle[48,50-52], and by increased vertical displacement of the center of mass[48] are often found (among other problems) in the gait patterns of children with cerebral palsy.

Our central hypothesis is that impairments in body structure and function result in changes in the dynamic resources, and that these changes in dynamic resources lead to direct and adaptive changes in the gait pattern (Figure 6). Consider first the impairments due to spastic cerebral palsy. We hypothesized that decreases in the ability of muscles to contract with sufficient and correctly timed force[53] would constitute a lost or diminished important resource for maintaining gait. In walking, research in both humans and robots has shown that the force is produced by the gastrocnemius-soleus muscles of the back foot pushing off as the front foot hits the ground[27,54]. The force needed is generated during a specific state of the gait cycle (in this case the push-off phase). The production of force at another time could either stop the motion or be ineffective in maintaining the movement.

An intuitive example would be a mother who is pushing her child on a garden swing. The mother pushes her child for a short part of the swing's trajectory as it starts the return from its apex (maximum amplitude and zero velocity). Such a strategy guarantees that the pushes will be delivered at the child/pendulum's natural frequency (determined by it's length and mass). For a constant amplitude swing motion a minimal amount of force is delivered to sustain the oscillation and keep the total amount of energy constant from cycle to cycle. A push at any other state will be less effective in allowing for the conservative passive resource to be useful: if the swing is moving toward the mother a push will serve to dampen the oscillation. If the swing is moving away from the mother, some of the force she has developed will be lost in 'catching up' with the swing. The force can be thought of as an escapement similar to that in a grandfather clock that releases energy from the spring or suspended weight at specific points in each gait cycle. Even if the force is sufficient in magnitude, poorly timed force would be ineffective or counterproductive.

In addition to changes in forcing capacity, it was also expected that the stiffness would change. Stiffer systems are harder to move, but at the same time they are capable of storing and regenerating elastic energy better than 'soft' springs. It was hypothesized that increased spasticity, cocontraction, and morphological changes would lead to increases in stiffness. Thus, the major impairments observed in children with spastic hemiplegia may be recast as changes in resource availability. To substantiate this claim, it must be shown first that there are changes in dynamic resources. For that purpose, we have used a model from which estimates of muscle force, soft-tissue stiffness, and the gravitational effects of the body can be made.

The contractile and elastic properties of muscles, elastic properties of soft tissues and the pendulum characteristics of the body and/or segments have been modeled extensively. In general, specific models have been adopted for a particular gait pattern; pendulum models for walking and spring models for running[25,29,55,56]. A notable exception is the hybrid pendulum and spring model of the swing leg during gait[57,58]. There is also a significant literature on a muscle model, first introduced by Hill[59], that beside contractile properties, also includes parallel and series elastic elements[2,60]. In our earlier modeling, (following the example of Turvey[58]), a single limb that is actively swung about the hip joint was represented by an ordinary (as opposed to inverted) pendulum that accounts for the gravitational pull

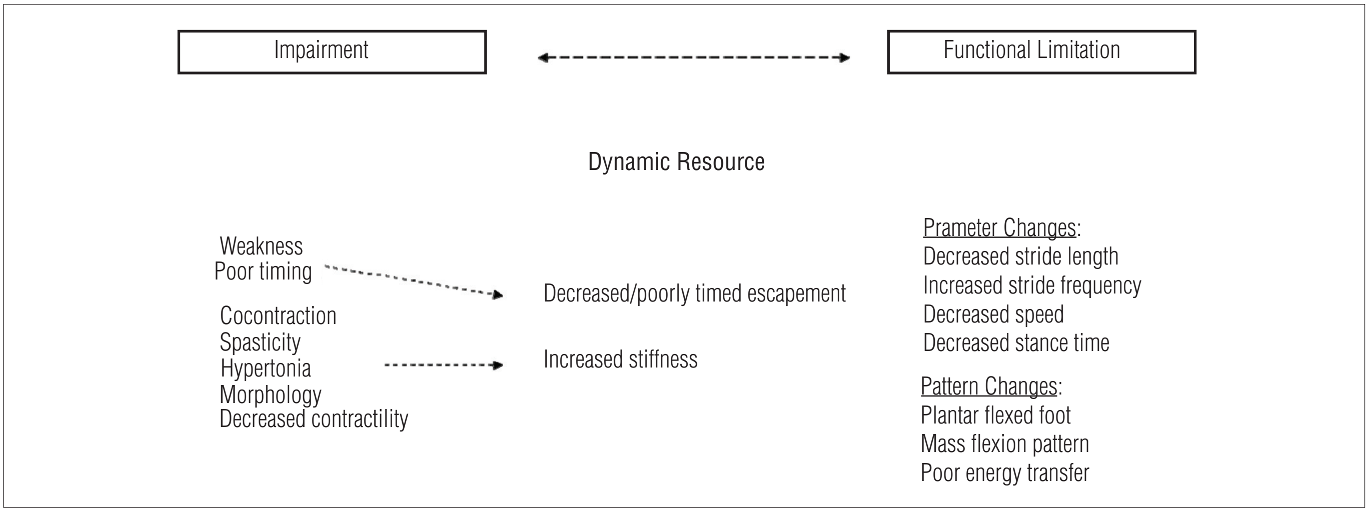

Figure 6. Understanding the relationship between impairment and functional limitations (activity limitations) or pattern through a dynamic interpretation. Loss of dynamic resources result in a change of pattern that reflects an adaptation to lost and gained resources (force production and elastic energy conservation).

on the limb (mass, length and acceleration due to gravity). The stiffness of a global spring of varying stiffness represents the tendency of soft tissues to be stretched (store elastic PE) and to return this energy at certain times in the gait cycle. In the swing leg pendulum this might be achieved by stretch on the hip flexors and knee extensors during the extension phase, and recoil as the limb begins to move into flexion - a similar escapement mechanism to that seen in a grandfather clock (Figure 7). An additional escapement (state-dependent forcing function) represents any concentric muscle contractions that are needed to offset energy losses in the non-ideal system. The model has been used successfully to predict preferred walking and running frequencies of quadrupeds, children[61] and adults[58,62,63]. When subjects are driven by metronome to walk at the predicted frequency at their preferred speed, metabolic costs are minimized, head stability is maximized and mechanical energy exchanges are maximized[63,64].

In further model development, we have applied a version of the model that treats the body as an inverted pendulum and spring to represent the oscillations of the body center of mass over the ankle axis during the stance phase of gait. The forcing function is assumed generated periodically and predominantly by the opposite limb during double support phase[21]. To simplify the model a single pendulum and forcing function are used for each limb (Figure 8). The model allows for the estimation of the relative contributions of muscle force, elastic potential energy return (reflected in the elastic spring's stiffness parameter), and the gravitational effect.

The behavior of the system is governed by an equation of motion that is of the following form:

Net Moment = Forcing Moment ± Gravitational Moment ± Stiffness Moment - Damping.

The model captures in a lawful way the interrelationship between task constraints, organismic constraints, and environmental constraints. In dynamic terms the *task* of walking is to maintain the forward translation of the body. The net (sagittal plane) moment captures the task in dynamic terms since it relates directly to forward translation. In order to continue

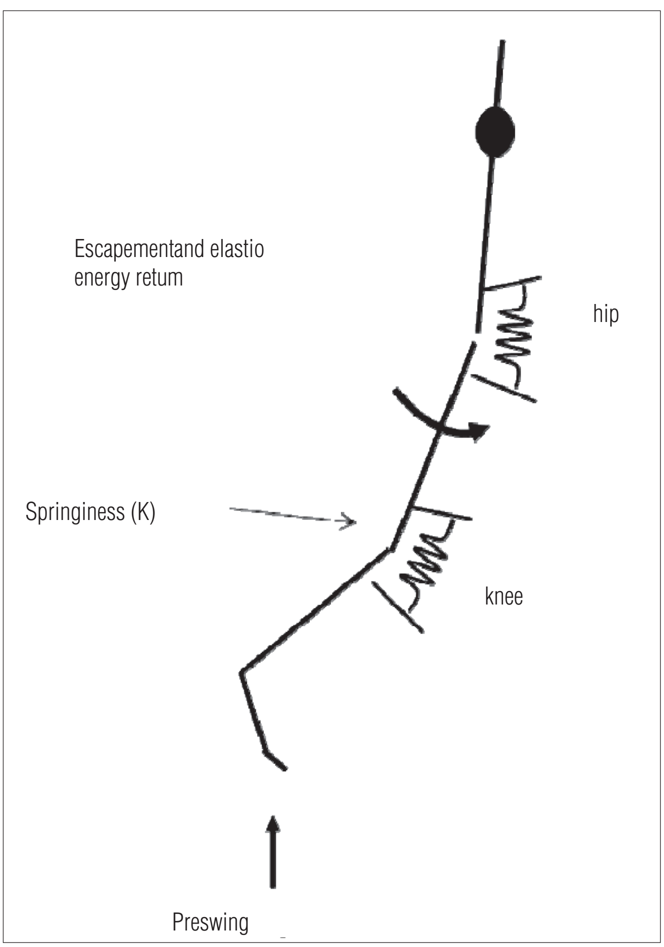

Figure 7. Example of active and passive mechanisms for leg swinging. Active contraction of the hip flexors for a short burst at the onset of swing facilitates return of passive spring energy in the hip flexors and knee extensors, and passive gain of kinetic from potential energy in the leg pendulum.

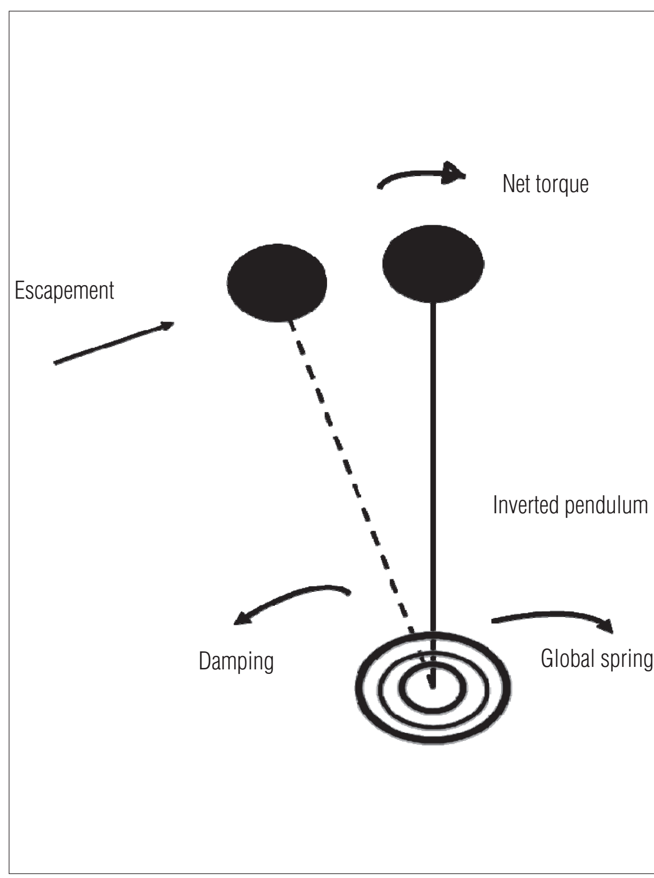

Figure 8. Escapement-driven inverted pendulum and spring (EDIPS) model of gait designed to capture the active and passive mechanisms involved in the stance phase of gait. Escapement energy for the inverted pendulum is provided by push-off of the contralateral leg. Passive transfers of energy are facilitated through the body pendula and soft-tissue springs. The simple 'global' model represents the overall effect of a number of potential mechanisms.

walking, the organism must produce an escapement torque to counteract energy losses, and it must conserve and exchange energy in its elastic soft tissue and pendulum properties. Potential and kinetic energy are interchanged between the segment and whole body pendular and spring properties in a gravitational environment. This process describes the interplay between the organismic and environmental constraints that constrain the movement pattern to walking or running and facilitate achievement of the task.

Another feature of the model equation of motion is that it may be informative about the nature and possibilities for compensation for individuals in which the dynamic resources have been compromised or altered. The idea that humans can turn themselves into different special purpose devices (SPD) is not new. We can turn ourselves into springs (for example when we bounce up and down or when we run (think of the leaf springs in prosthetic devices that are used to help amputee athletes achieve spectacular sprint times). We can turn ourselves into effective shock absorbers when jumping from heights, and we can turn ourselves into multiple compound pendulums for walking. Since the net moments are insensitive with respect to their sources, the model allows for flexibility of function as resources can be assembled in different ways. Thus, for example, insufficient muscle force production could be compensated for by an increased stiffness component to produce the same net moment on the body[1a].

Experimental results: Estimating dynamic resources in children with spastic cerebral palsy

1) The ordinary (swing leg) hybrid pendulum-spring model

Our first experiment on children with cerebral palsy as subjects was to determine if their preferred walking frequency was predicted by the ordinary (swing-leg), hybrid pendulum-spring model that had been observed in healthy adults and children[62,63]. The model assumes that individuals walk at preferred frequencies that are predictable from the natural or resonant frequencies of their lower limbs. Natural frequency of a pendulum is determined by its length that determines the pendulum stiffness. When a spring is added to the system, its stiffness can be interpreted as reflecting cocontraction or isometric contraction against gravity in the system. Preferred walking frequencies are predicted when the spring and pendulum stiffness are equal. It was shown that, in contrast to typically developing children, the model predictions underestimated the preferred walking frequency of the children with cerebral palsy, and that the preferred rather than the predicted frequency resulted in minimal metabolic cost and greatest head stability (as measured by deviations from a sinusoidal trajectory across gait cycles). Since natural walking frequency is based on the anthropometric characteristics (length) and biomechanical stiffness, we suspected that an increase in stiffness due to impairments resulted in the higher natural frequency of walking. To assess the stiffness component we calculated the ratio of the elastic stiffness to the gravitational stiffness that would be necessary to accurately predict the preferred walking frequency demonstrated by the children with CP. In quadrupeds, typically developing children and adults a highly accurate prediction of preferred walking frequency was found when a 1:1 ratio between the elastic stiffness and gravitational stiffness was assumed. In contrast, the children with CP required a mean ratio of 1.43:1 to predict the preferred frequency, indicating a stiffness increase of 43% in the children with CP. This suggests that the model is capable of quantifying the increased stiffness due to impairments in functional movements.

Based on these findings we used the ordinary pendulum/spring model to assess the stiffness characteristics of children with CP compared to their non-disabled counterparts, and between the more involved and less involved limbs during a leg-swinging task used previously with healthy adults[65]. The individual has the body supported and is asked to swing the leg back and forth in a comfortable manner. From the preferred swinging frequency it is possible to use the model to estimate the limb stiffness. We predicted that children with CP would show greater stiffness than their non-disabled counterparts, and would show greater stiffness in the more involved versus the less involved limb. The results were as predicted[66]. Children with CP showed greater stiffness in the more involved limb compared to the less involved limb, and both limbs demonstrated greater stiffness than the limbs of the non-disabled children. These results confirmed the capability of the model to differentiate the stiffness even in the relatively mild cases of spasticity in the sample group (between 0 and 2 on the Ashworth Scale).

[1a] Special Purpose Devices are assembled using multiple musculoskeletal degrees of freedom imbued with task-specific dynamics. In jumping two-legged and absorbing shock, each leg acts as though it has only a single degree of freedom (leg length [defined as the distance from hip to ankle]) with damped mass-spring dynamics, and with the two legs coupled to move in-phase with one another. We can convert this shock absorbing device into a bouncing device (pogo stick) by changing the damped mass-spring dynamics into a limit-cycle dynamics through the addition of a push-off escapement function. We can turn ourselves into a walking device in which each leg acts as though it has only a single degree of freedom (leg angle [defined as the angle from hip to ankle]) with limit-cycle dynamics (damped pendulum + escapement), and with the two legs coupled to move out-of-phase with one another. For running, each leg acts as though it has two degrees of freedom (leg angle and leg length); in addition to the angular limit cycle dynamics used during walking, running entails leg-length pogo-stick-like limit cycle dynamics with escapement impulses during push-off. As with walking, the two legs are coupled to move out-of-phase with one another. Finally, for both walking and running, the arms act as pendular limit cycles that enter into frequency and phase relations with each other and with the legs in a locomotion speed-dependent manner.

The method for calculating stiffness through the model is simple because it is calculated from the preferred frequency of walking that can be simply obtained by counting steps within a designated time period. Furthermore it allows comparisons to 'normal' which the model characterizes as having a 1:1 ratio of spring:gravitational stiffness.

Potentially the method could overcome two clinical problems of evaluation. First, spasticity, defined as a hyperactive stretch reflex, is considered the most common motor impairment in children with cerebral palsy. Consequently, a great deal of effort has been made clinically and in research to quantify spasticity[42,67]. However, it has been recognized for some time that spasticity is but one of a number of neurophysiological, and morphological changes that influence the movement patterns[68,69]. Research has shown that activity limitations are influenced by a number of factors that including spasticity, muscle weakness and/or poor power production[3]. Morphological changes in muscle and connective tissue[68], and coactivation of antagonist pairs[38] also influence functional capabilities. Measuring spasticity in isolation may be neither plausible nor desirable for functional assessment.

Second, attempts to quantify spasticity have been limited to passive tests. Clinically, tests such as the Ashworth Scale are typically used to measure passive resistance to muscle stretch. In the experimental situation, mechanical measures using forces that passively push the foot backward and forward sinusoidally have been used to assess spasticity and other conditions producing hyper-and hypotonia (for review see[70]). There is evidence to suggest that such passive measures of spasticity may not generalize to active voluntary movements because of the modulating effects of supraspinal influences on the stretch reflex. Passive assessments, therefore, may not directly provide the most relevant measures for active and functional movements. Stiffness is a more general measure that describes the overall effect of the spasticity, changed morphology, and cocontraction on the musculoskeletal system during the performance of an activity such as walking. Stiffness, like spasticity is a measure of the resistance to displacement. However, it is not restricted to only the effects of spasticity, and based on our research we discovered that it is measurable during functional movements.

2) The Escapement Driven Inverted (stance leg) Pendulum and Spring Model (EDIPS)

In many biomechanical models, the ankle is assumed for simplicity's sake, to act as an axis of rotation over which the body CoM oscillates during the stance phase of gait. The model can be used to estimate stance phase soft tissue elastic stiffness and pendular gravitational stiffness, and the escapement force. We used such a model to estimate these variables in each leg of children with spastic hemiplegia (0-2 on the Ashworth Scale) at different stride frequencies[71] and speeds[72,73]. In all cases, the more involved limb showed greater stiffness than the non-involved limb, and greater stiffness than either leg of typically-developing children. There was also lower force production in the involved leg, compared to typically developing children and to the less involved side. Interestingly, the less involved side showed greater force production than the typically developing children. Children with CP used this force not just to propel the CoM a greater distance along the line of progression, but also to raise the CoM higher. This allowed the child to drop the body weight more forcefully onto the stiffer involved side (in the way that a runner would) – a force that is needed to compress the stiff leg spring and potentially achieve greater energy return. Very little progression of the CoM was achieved while the load was on the involved side. Thus, while the less involved limb acted as an enhanced force-generating pendulum, the involved side behaved very much like a vertical spring. The resulting asymmetrical gait pattern has been described as a 'pendulum and pogo stick' pattern with each limb using its respective different dynamic resources to ensure continued forward progression[72]. The child with hemiplegic cerebral palsy has discovered a different special purpose device (SPD) for each limb, and the emergent asymmetric gait pattern provides the means to make each SPD functional.

Some of the observed changes in walking pattern are entirely predictable from the model. In the model a decrease in forcing results in a decrease in stride length (or more precisely, the amplitude of the inverted pendulum's oscillation), an increase in stiffness predicts an increase in frequency (cadence). However, the children also discovered patterns that help them utilize the changed resources. For example, the non-involved leg raises the CoM higher to 'drop' the body weight onto the involved leg's, plantar flexed foot at initial contact thereby enhances the body's capability to store and recover elastic potential energy (Figure 9). We believe these children, by a process of exploration, discover these functional adaptations of their locomotor pattern.

Unfortunately, these discoveries may lead to deleterious adaptations in the resources. As children with CP get older, they become stiffer through morphological changes in tissue properties that result from using the leg like a pogo stick (an example of form following function). In the gastrocnemius-soleus, tendons become relatively long compared to muscle that has fewer contractile elements, becomes shorter, and has an in-growth of noncontractile tissue. In essence we are arguing that abnormal gait patterns, morphological changes, and eventual degeneration of joints are outcomes of functional maladaptations that nevertheless allow children to successfully locomote. There are a number of observations that support this conjecture. First is the fact that

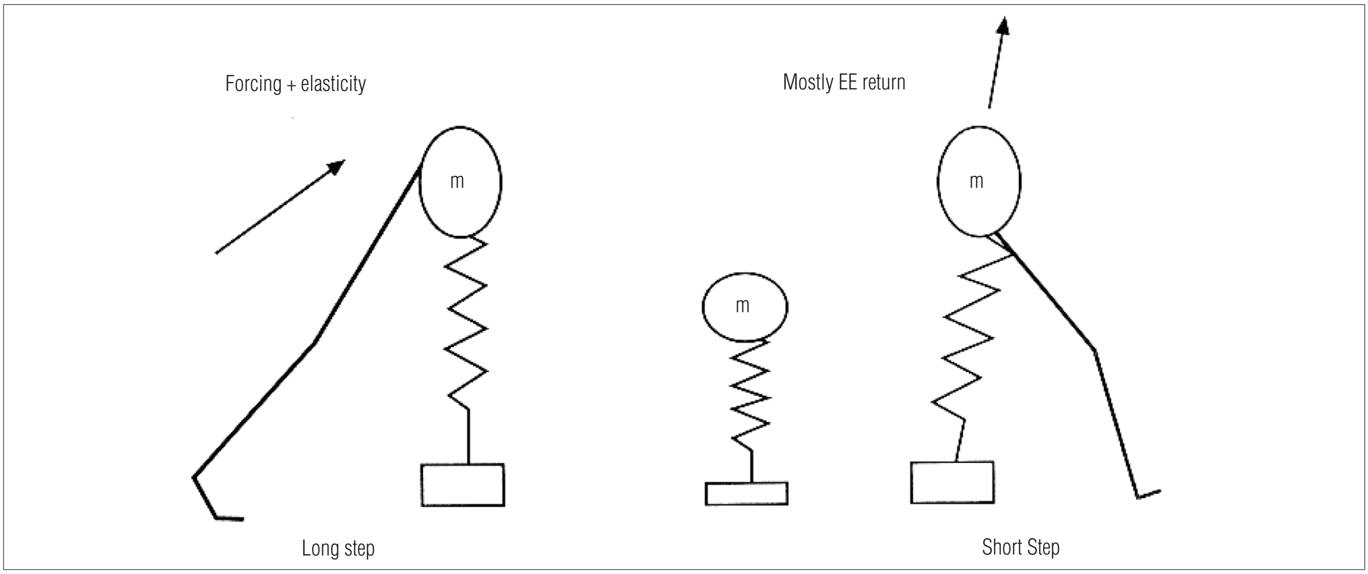

Figure 9. Hemiplegic gait; 'the pendulum and the pogo stick' (Fonseca et al.72). Spring represents the action of the affected limb while the stick represents pendulum action. Data show that the non-affected limb produces greater impulse than seen in typically developing children. Part of the force is used to raise the CoM so that the body weight can be dropped onto the stiff spring, thereby facilitating elastic energy return.

children with spastic cerebral palsy often demonstrate a toe walking pattern that is initially not due to a contracture of the G-S. It is often possible to have the young child with CP stand flat-footed, and to passively dorsi-flex the foot. Second, children with CP often go undiagnosed *until* they begin to walk[74], that is, until they recruit the resources that allow walking to happen. In the early years after the onset of walking, it may still be difficult to elicit a spastic response.

If this conjecture is correct it calls into question conventional treatments that attempt to reduce spasticity through medications and surgery, and/or to increase range of motion (through serial casting, or tendon-lengthening procedures). Conversely, if increased stiffness is an adaptation to a decrease in the ability of the G-S muscle group to contract with sufficient force and at the right time, it would suggest that we should direct treatment at remediating this lost resource. If this were done, the need for the increased stiffness as an adaptation will be diminished. Thus, we suggested that treatment of children with these features should aim to normalize resources rather than normalize the motor patterns themselves. To test this idea, we used functional electrical stimulation (FES) as a way to enhance the force production of the G-S muscle group during walking in children with either hemiplegic spastic CP or diplegic spastic CP.

An experiment designed to 'normalize' dynamic resources in children with CP.

FES, triggered by foot switches, turned on during the time that the G-S would be normally active. It was predicted that FES would enhance the escapement forces (at push-off) generated. Further, it was predicted that the FES would decrease the need for the required adaptation of increased stiffness, resulting in lower stiffness on the stimulated limb. This second prediction would work 'on-line' only in young children in which increased stiffness is a control 'choice'. In older children, the morphological changes would ensure a much longer time for readaptation. Using the EDIPS model, the variables of interest were estimated in a balanced design in which the subjects were given both a FES and non-FES condition. Results were surprising for two reasons. First the impulse generated was much larger than would have been expected from the intensity of the stimulation that, because of the poor tolerance of many of the children was barely above motor threshold when the stimulation was first applied[75]. Second the stimulated limb showed a small but significant decrease in stiffness[76]. The first finding suggests that the FES serves to facilitate/enable the natural response to contract at the appropriate state of the system. Further, it may be that FES may be 'teaching' the nervous system when and with what force the muscle contractions that are needed for the escapement. Proof of this notion would be shown if a normal pattern of gait is maintained after removal of the stimulus. Clinical observations suggest that this is indeed the case, and that the effects last in the long term (Carmick, 2010, personal correspondence)[77]. The second finding supports the notion that stiffness is an adaptive, rather than primary response to upper motor neuron disease. The findings in the clinical literature[78-81] that show a more normal pattern of locomotion using FES in this way support the notion that treatments should be aimed at 1) identifying the underlying neuro-mechanical mechanisms during activities such as locomotion, and 2) focusing treatment on the primary dynamic resource(s) that is/are compromised or lost due to the UMN disease process.

Dynamics of Parkinsonian gait

Parkinson's Disease (PD) is a severe and progressive neurodegenerative disorder, characterized by insidious onset. The first signs become clinically manifest when about 60 to 80% of the dopamine producing cells of the substantia nigra have degenerated (e.g., Martin[82]). Despite dopaminergic medication, after some time the patients face a relentless deterioration in mobility and activities of daily life (ADL) that can eventually result in need for custodial care. The clinical hallmarks of the disease include difficulty initiating movement (akinesia), slowness and difficulty in maintaining movement (bradykinesia), stiffness in arms and legs (rigidity), inability to make purposeful motions in the trunk (axial apraxia), and a pathological tremor at approximately 5 to 6 Hz (e.g., Martin[82]; Morris[83,84]). In the aging population the prevalence (between 128 to 187 out of 100,000) and annual incidence (20 per 100,000) in the United States is increasing[85]. The medical treatment of PD mainly consists of dopamine replacement therapy, dopamine agonists and deep brain stimulation requiring surgery. After a variable number of years medical treatment becomes ineffective and the severely disabled patients with PD may have to spend the rest of their lives in extended care facilities. If physical therapy can positively influence ADLs and quality of life in patients with PD, this could imply that (more intensive) use of medication can be postponed. As a result patients might benefit longer from less intensive regimens of medication, and would be less quickly referred to extended care facilities.

One of the findings of research in the effects of physical therapy is that externally provided rhythmic visual stimuli (e.g., [82,86,87,88,89]) and self-provided visual cueing[90,91] improve the coordination of walking in patients with PD. Thirty years ago, Martin[82] observed that spatially regular ("rhythmic") transverse white parallel stripes on the walking course had a positive effect on gait initiation as well as on the coordination of walking. In a study involving six patients with PD, Forssberg[86] asserted on the basis of visual inspection that regular placed white sheets of paper improved stride length (by more than 100%) as well as walking velocity. Mestre[87] confirmed this finding in one patient with Parkinsonism without clinical signs of rigidity and tremor, who suffered from freezing problems during walking. The effects of five different distances (i.e., 15, 30, 60 120 and 240 cm) between successive stripes on freezing episodes were investigated. Mestre and his colleagues observed consistent freezing at an inter-stripe distance of 15cm, no freezing in the 30cm condition, and intermediate degrees of freezing at 60, 120, and 240cm[87]. These findings suggest that there is an optimal inter-stripe interval (30cm) in preventing the occurrence of freezing behavior, and leads to the question of whether effective frequencies for stimulation may be predictable.

In an attempt to identify and classify gait disorders in neurologically disabled individuals, the ability to adapt coordination patterns according to particular task and environmental contexts (flexibility of movement patterns) and the stability of the corresponding rhythmic locomotor patterns for intersegmental relative phase and frequency ratio were studied from the perspective of nonlinear coordination dynamics (e.g.,[18]). In this framework coordination patterns are characterized by order parameters that describe the coordination between movement of body segments (i.e., phase and frequency relations). By systematically manipulating a control parameter (e.g. walking speed or frequency) changes are brought about in the order parameter (e.g.,[20]). Using this approach it was found in healthy subjects that, when systematically varying walking speed from 0.2 to 1.5 m/s, a transition from a nearly in-phase (about 20 degrees) relation between pelvic and thoracic rotation as well as between arm and leg movements to closer to out-of-phase (about 120 degrees) relation occurred at about 0.7 to 1 m/s (e.g.,[22,28,92]). Similar transitions between pelvic and thoracic rotations as well as between arm and leg movements were observed when systematically increasing frequency of Rhythmic Auditory Stimulation (RAS) from 0.8 to 2.4 Hz imposed on the step. At different constant walking velocities (0.4, 0.8 & 1.2 m/s) the change from an in-phase to an out-of-phase relation emerged at about 1.6 Hz step frequency.

Wagenaar and van Emmerik[18,93] have also presented evidence that with increasing walking speed (and frequency) the coordination of arm and leg movements changes from a pattern in which the arms are dominantly synchronized with the step frequency (that is, a 1:2 frequency relation between leg and arm movements) at slow walking speeds (0.2 - 0.8m/s), to a pattern in which arm movements are locked onto the stride frequency (that is, a 1:1 frequency relation between leg and arm movements) at faster walking speeds (0.8 – 1.4m/s). In both coordination modes the arms move mainly at a frequency ranging from 0.8-1.1 Hz, suggesting that the two modes at different walking speeds reflect the arm's preferred frequency. Calculation of the resonant frequencies of individual arms (about 0.98 Hz) and legs (about 0.85 Hz) with a simple pendulum equation [21,62,64] revealed that preferred step- or stride frequency occurred could be adequately predicted as the arm's resonant frequency in the slow walking pattern (1:2 at 0.5 m/s), and by the legs resonant frequency in the faster walking pattern (1:1 at 1.2 m/s)[28]. Overall, the results indicate that different patterns of coordination, as shown by changes in frequency coupling and phase relations, can exist within the human walking mode. The transitions in phase and frequency relations between pelvic and thoracic rotation as well as between arm and leg movements emerged gradually, with an increased instability at intermediate walking velocities[22,92]. These findings reflect the highly non-linear nature of gait as a function of walking velocity and frequency (see[94]).

In individuals diagnosed with Parkinson's Disease (PD) manipulations of walking speed and frequency have led to the identification and classification of disordered coordination patterns in walking in terms of their flexibility and stability (i.e.,[22,95]). For example, a number of individuals with PD had a reduced ability to change their walking patterns coordination patterns in the walking mode (reduced adaptability), and the coordination patterns displayed were less variable compared to healthy subjects. Significant correlation coefficients were found among reduced adaptability, hyperstability of walking patterns, and rigidity (assessed by means of the UPDRS-scale)[23,24].

Our research findings clearly support the rehabilitation potential of the approach taken. A number of patients demonstrated improvements in movement coordination (i.e., increased ability to switch between walking patterns and less (hyper) stable walking patterns) as a result of walking speed manipulations[18]. In addition, patients showed improved coordination patterns when instructed to lock their leg movements onto the frequency of a rhythmic auditory stimulus (RAS), particularly when they were instructed to synchronize their legs as well as their arms to the frequency of the rhythm[28,96]. In cases where the manipulation of the control parameter was ineffective in allowing patients to make transitions between walking patterns, it was found to be related to relatively hyperstable walking patterns in PD.

In attempting to understand the relationship between impairments and function using the dynamic resource model, the data from these studies on PD suggest that displayed bradykinesia, rigidity, and axial apraxia are clinical manifestations of a system that has increased stiffness. In the pendulum-spring models, a change in frequency is directly related to a system's stiffness, Thus, as the pendulum-spring models would suggest, manipulation of walking frequency (as a control parameter) may have influenced stiffness and thereby allowed for improved functional walking capability in these patients. Further studies using the model to estimate stiffness before and after treatment would support this hypothesis.

Summary

We have proposed a systems approach to control and coordination for unpacking the relationship between levels of the Nagi/ICF models. In particular, we have focused on the usefulness of the tools from dynamic systems approaches for understanding the mechanisms that underlie the often complex relationships between impairments, functions, and functional adaptations. Children with cerebral palsy serve as a good example of the usefulness of the approach because gait patterns that arise are stereotypical and particularly difficult to treat effectively. Using a similar way of thinking about PD, it is possible to not only to choose effective intervention strategies ('control parameters'), but to also perhaps to predict the optimal values for the control parameter based on an individual's anthropometric characteristics. In cerebral palsy, the results of this enterprise lead to a theory and research-driven approach to evaluation and treatment that often flies in the face of conventional wisdom.

Implications for rehabilitation

The following principles of evaluation and treatment are suggested by the systems/constraints approach

1) The systems approach implies that if we wish to understand the relationship between impairments and compromised body functions, we must consider the impact of different tasks and environments in relation to the organismic constraints; *perhaps better, we must study the impairments in body functions and activity limitations in the organism-environment synergy, that is, during task performance (activities)*. As physical therapists we must therefore consider mismatches between the organism's resources and the requirements of the tasks and the environmental influences.
2) The tools of the dynamic systems approach (biomechanical modeling, coordination dynamics) and a thorough knowledge of the functional anatomical constraints for specific tasks can help us to make hypotheses about the mechanisms that underlie the relationships between levels of the Nagi/ICF classification systems.

In addition, the findings of our own research suggest the following:

1) Non-standard movement patterns *are not necessarily dysfunctional* movement patterns. For example, children with cerebral palsy discover ways of using their available dynamic resources in movement patterns that are mechanically sound and metabolically economical. Does this suggest that we do not treat the problems of cerebral palsy? While the solutions discovered by children with cerebral palsy may work in the short term, there may be untoward long and short-term consequences. For example, a child who essentially uses a running-like gait pattern is susceptible to early fatigue, and accelerated wear and tear on the

joints[97,98]. In any case, the solutions discovered lead to easy fatigue, itself a constraint on locomotor ability.

2) If changes in dynamic resources (DR) as a function of pathology are the cause of non-standard and potentially dysfunctional movement patterns, our findings suggest that treatment should be aimed at the DR level. For example, in individuals with Parkinson's disease the hyperstability reduces the ability to switch between slow and faster walking patterns. If, therefore, the appropriate muscle groups are unable to supply the right amount of force at the right moment, then we might wish to use treatment methods to improve that capability. Several published randomized controlled trial on the effects of rhythmic auditory stimulation (RAS) provided evidence that physical therapy can facilitate walking ability. A home exercise program focusing on facilitating gait by means of RAS showed significant improvements in walking speed, spatio-temporal parameters of the stride, as well as EMG activity of the anterior tibialis and vastus lateralis muscles in comparison to a self-paced (without metronome) home exercise program and a no-treatment condition[99].

Clearly, attempting to facilitate muscle force production at the right time is critical. Another promising approach is that being pioneered by Judy Carmickusing Functional Electrical Stimulation (FES) of the G-S during the stance phase of gait[78,79,81]. If the G-S group is stimulated during the propulsive phase of gait greater dorsi-flexion of the foot, including a relatively normal heel strike, is observed. How can a muscle that normally causes plantar-flexion produce a dorsi-flexion response? The apparent paradox is solved through interpretation within the model dynamics. Since the initial problem of weakness in the forcing was diminished through stimulation, the need for spring-like adaptation in the gait pattern was no longer necessary, and a more normal gait could be assumed.

1) Conversely, the notion that preferred gait patterns may be adaptations that facilitate the use of available dynamic resources speaks against certain types of intervention strategies. For example, consider a number of invasive and non-invasive intervention strategies. Treatment of cerebral palsy gait disorders is often aimed at directly normalizing the gait pattern. Serial casting of the ankle, ankle-foot orthoses, tendon-lengthening procedures, muscle relaxants, and neuroinhibitors are treatments designed to normalize the gait pattern. An alternative view is that the plantar flexed foot on ground contact is an adaptation to facilitate elastic energy return. If this is the case, intervention strategies that seek to normalize gait may result in child having to use less functional movement patterns or even to lose locomotor ability. For example, clinical observations suggest that tendon-lengthening may rid the patient of spastic gait but replace it with crouch gait. The problem with normalization approaches is that they focus on symptoms rather than causes. If the cause of the disordered gait pattern is a change of dynamic resources resulting from the pathology, the solution must address the problem at the level of those resources.

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