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RESEARCH REPORT

Solution space: Monitoring the dynamics of motor rehabilitation

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ABSTRACT

This article presents and discusses a perspective on the concept of "solution space" in physiotherapy. The model is illustrated with a subjective assessment of the way movements are performed and an objective quantification of the dynamics of the recovery process for a patient with a knee injury. Based on insights from the domain of human motor control, solution space is a key concept in our recovery model that explains the emergence of a variety of adaptive changes that may occur in the movement system recovering from an injury. The three dimensions that span the solution space are: (1) information and control processes; (2) time; and (3) degrees of freedom. Each dimension is discussed within the context of feasible physiotherapeutic assessments to identify and facilitate desirable behavioral patterns or bypass emerging but undesirable behavioral patterns that could impede both short- and long-term recovery. Central to this article is our view on the relationship between the recovery process and the three dimensions of the solution space, which determines the model's usefulness as a motor-rehabilitation monitoring tool.

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ACL; Motor-rehabilitation; Musculoskeletal; Solution space

Introduction

Every successful action is a demonstration of an impressive number of skills that people have mastered seemingly effortlessly while participating in daily life. Although based on past experience, once initiated, actions unfold in an uncertain future. The dynamics of complex actions allow us to cope with a certain amount of unpredictability during task performance, which guarantees the successful future outcomes of our actions despite unexpected changes in movement conditions. The dynamics of human actions are determined by several factors that mutually interact in a time-dependent manner, within a task-dependent interaction with the environment (Clark, 1995; Newell, 1986). Some aspects related to individual factors include anatomical structures, physiological processes, body height and weight, perception, action, adaptation, compensation, development, and learning. A specific movement task can specify the action target, the outcome or the indicated manner and means of the task performance. Environmental determinants consist of external factors, such as gravity, temperature, light, and cultural conventions. Understanding the probable interactions among these different factors is of great importance, both for physiotherapists and the research field of complex adaptive systems in which physiotherapy is embedded (Huang et al., 2011; Lamoth et al., 2002). The constraints-led approach that we advocate here has its roots in the dynamical systems approach, ecological psychology, the uncontrolled manifold hypothesis, and the optimal feedback control theory (Kelso, 1997; Renshaw, Davids, Shuttleworth, and Chow, 2009; Scholz and Schöner, 1999; Todorov and Jordan, 2002). Within the dynamical systems approach, the "state space" refers to a Euclidean space in which the variables on the axes are interrelated by a first-order differential equation (e.g. velocity (Y) and position (X) time functions). By contrast, with the concept of a solution space we aim to capture three different dimensions, reflecting the underlying mechanisms involved in the recovery of the movement system after an injury. The similarity between "state space" and "solution space" is that the state of both systems is represented as a vector within the space.

The insights afforded by the proposed approach are not only indispensable for physiotherapists to understand how humans move to attain an intended goal, but also to enable them to appreciate the underlying mechanisms that will allow patients to recover from an injury to their movement system and to ultimately regain their ability to participate in daily life. Behavioral flexibility (Harrison and Stergiou, 2015) is one of the core concepts explaining

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the emergence of a variety of generally appropriate movements during the recovery from an injury to the movement system. We define behavioral flexibility as the phenomenon that humans can make smart and fast adaptive choices to successfully perform a movement task under varying conditions, implying that we are able to rapidly select and generate suitable solutions from a large movement repertoire. This capacity enables us to utilize adaptive processes and compensatory strategies to swiftly vary or modulate our movements to cope with a certain degree of unpredictability as the movements unfold. Here it must be noted that we define adaptation as the process of recovering from an imbalance of the movement system caused by external factors, while compensation is defined as trade-offs or covariations among internal factors in a system. Bernstein (1967) assumed that the abundance of solutions for the same action stems from the fact that the compositionally complex musculoskeletal system contains an impressive number of interacting physical components. The near-infinite number of combinations these physical components offer (i.e. physical degrees of freedom) and the very large number of interactions that can take place between these components (i.e. functional degrees of freedom) can be deployed for the achievement of a movement goal (Li, 2006). This implies that "all roads lead to Rome", in that we have at our disposal countless ways to reach a movement goal. The "solution space" accordingly represents an individual's adaptive motor potential to compensate for the (un)predictability of the motor system, the task, and the environmental interactions (Hong, 2007). The concept of a solution space thus refers to a three-dimensional Euclidean space that represents the dynamics of the underlying processes contributing to the exploration of possible movements during the recovery of the movement system after an injury.

The human potential to adapt to the environment has, in a more general sense, recently received growing attention in the health domain. In an editorial in the Lancet (2009) and in further explorations by Huber et al. (2011), it was posited that health is not a fixed status, but is instead characterized by one's ability to adapt to the environment. Health should hence be seen as a dynamic concept that varies for every individual, depending on his/her circumstances. Solution space, as introduced here, should be viewed in the same vein (i.e. as a usable tool for physiotherapists to monitor the rehabilitation dynamics of the human movement system after an injury).

Besides considering the essential activities an individual needs to be able to perform to function independently and unaided, the physiotherapist relies on the observation, recognition and description of the ways in which actions are performed. A qualitative description of the performance of relevant activities not only shows whether there is recovery, but also highlights potential strategies to enhance the recovery process. Consider a patient who comes limping into the therapist's office; with this behavior, the patient almost certainly signals that something undesirable has happened, and the practiced eye can already deduce which part of the motor system is likely to be affected. In due course, improvements in the patient's gait likewise tell the same expert eye that recovery has taken place. Furthermore, the manner in which the activity is being executed also provides guidance on how the recovery of the action can best be supported, a highly relevant factor for treatment, with a central role being reserved for the concepts of residual motor capacity (RMC) and solution space.

When assessing a patient's RMC, rather than focusing on the limitations that result from the medical condition, we must establish which motor actions the patient is still able to perform. To this end, the therapist needs to gauge the patient's current physical activity level, range of motion, self-reported quality of life, and the various ways in which the patient can still execute tasks. A careful delineation of the way motor actions are actually performed is an important element in defining the behavioral flexibility of the neuromotor system, enabling us to place recent scientific insights concerning neuromotor processes and redundancy control into a physiotherapeutic context (Bosga, 2008). Knowledge of these control processes provides the physiotherapist with information regarding the underlying mechanisms guiding patient actions during recovery from an injury to their movement system (i.e. the aspects of an individual's solution space that they currently utilize and those that can still be reclaimed and exploited). Helping the patient optimize this exploitable space then serves as the goal of the therapeutic intervention.

Solution space

The authors (Meulenbroek and Bosga) defined three dimensions that span the solution space: (1) information and control processes; (2) time; and (3) degrees of freedom (Figure 1). In Figure 1, the vertical axis represents the "information and control processes" dimension, with the bandwidth (very fast > 21 Hz, fast 9–12 Hz, and slow 1–8 Hz) of associated neuromotor processes. This dimension is related to the concept of "efficiency". The horizontal axis shows the "time" dimension in milliseconds, seconds, minutes, hours, and days. This dimension is characterized by the theoretical concept of short- and long-term "adaptation". The third dimension represents the "degrees of freedom" of the effector system (shoulder, hip, knee, and ankle) and is related to the concept of "compensation".

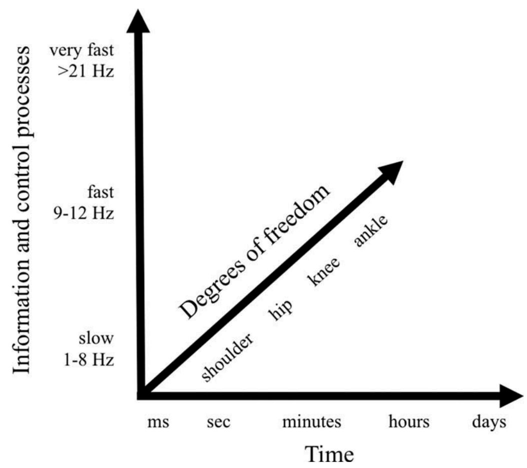

Figure 1. A three-dimensional representation of the "solution space", with the vertical axis representing the "information and control processes" dimension (i.e. very fast > 21 Hz; fast 9 to 12 Hz; and slow 1 to 8 Hz) of associated neuromotor processes, the horizontal axis representing the "time" dimension (i.e. milliseconds, seconds, minutes, hours, and days), and the third dimension representing the "degrees of freedom" dimension (i.e. shoulder, hip, knee, and ankle).

Information and control processes dimension

The information and control processes in the first solution-space dimension refer to the efficiency of the information processes involved in the execution of motor actions. Different types of control processes may guide movements, such as the fast, proprioception-based processes, the somewhat slower visual control mechanisms and the even slower cognitive monitoring system. Impairment of the movement system may cause motor skills that are normally automatized to be excessively visually monitored, which may inhibit the timely development of fast adaptive processes and compensatory strategies. Physiotherapists should recognize the relatively slower or relatively faster control processes of movement generation as components of the solution space. Guiding the patient to shift focus from their own body (internal focus) to their environment (external focus) should create conditions in which the patient dares to rely on proprioception-based automatic control processes again, promoting smooth, efficient, and flexible movements. For example, when the patient displays excessive visually guided motor control during movement execution and is asked to simultaneously perform a secondary task or is distracted by the physiotherapist, does the patient's motor performance become more automatic? Spontaneous, fast, automatically controlled movements that are initiated and concluded with confidence are therefore held to be characteristic of a functional motor system. After all, the patient must eventually be resistant to disturbances caused by environmental circumstances. The spectrum of observations that control movements, ranging between very fast proprioception-based processes to very slow cognitive control mechanisms, is particularly relevant to this dimension.

Time dimension

The second, temporal dimension defining the solution space relates to the adaptation to and spontaneous recovery from an injury to the movement system. Taking the adage "time heals all wounds" as the starting point, we implicitly make a pact with natural recovery, a process which is indicative of a functional biological system. Upon injury, the patient will instantly adjust their movements to avoid discomfort or pain. These rapid adaptations to the injury in the short term are inevitable and biologically meaningful because they will presumably prevent further damage to the musculoskeletal system. During the subsequent stages of the recovery process, the patient's movement system will continue to display a variety of appropriate movements either emerging spontaneously or co-initiated by physiotherapy. It is crucial that therapeutic interventions enhance both the short- and medium-term recovery processes within the scope of a patient's solution space, which is also determined by the patient's motor learning ability. Is the patient capable of restoring balance after a perturbation during the execution of a balancing exercise, for instance? To what extent is the patient able to modify their movements or learn new movements? Unfortunately, in some patients the natural recovery process fails or is delayed, leading some to adopt behavioral patterns that will impede long-term recovery, such as bad or rigid motor habits. A bad habit is defined as an adaptive behavior that was initially appropriate during the early stages of the recovery process following a musculoskeletal injury but persists after healing has occurred, becoming detrimental to further recovery (Walter and Swinnen, 1994). Here, preventative physiotherapy is indispensable in preventing the development of these bad habits or rigid movements. The time at which important milestones of the recovery process are reached is particularly relevant for this dimension.

Degrees of freedom dimension

The third dimension of the solution space comprises the degrees of freedom of the neuromotor system and is associated with compensatory control strategies among interacting components of the compositionally complex musculoskeletal system, such as joints, muscles, fascia, bones, ligaments, and limbs. In a functional motor system, this variability hinges on the flexible organization of the neuromotor system allowing sufficient variation in available movements. Finding a task-dependent combination of interacting components to achieve a selected movement goal is an exciting puzzle, often with unexpected results (Carr and Shepherd, 2006). There are always several ways to perform a movement task, and it is the responsibility of the physiotherapist to expertly guide patients to explore and exploit potential compensation mechanisms in their motor systems. In this dimension, the spectrum of observations regarding the unfolding of movements over time is again the most relevant factor, particularly in terms of the extent to which movements are performed in a rigid or a flexible manner.

The dimensions discussed above are all vital components in the dynamics of complex biological systems, and thus taken to be indicative of an adaptive neuromotor system. To determine a patient's potential for recovery, the proposed solution-space model accordingly considers all the observable interactions among the information and control processes (i.e. efficiency), time (i.e. adaptation), and degrees of freedom (i.e. compensation). It is the role of the physiotherapist to identify and exploit a patient's biological and biomechanical potential during the recovery process to help restore the adaptability of their movement system.

In the following paragraphs, we will illustrate how the concept of solution space can be implemented. We will first introduce a patient with a knee injury, detailing the diagnostic assessment by the orthopedic surgeon and the initial subjective assessment of the way the patient performed movements, with the main goals of the intervention and the expectations of the physiotherapist being explicated. Next, from an activity-level perspective and in chronological order, we will report the subsequent subjective assessments of the way movements were performed over the course of the patient's recovery. We will elaborate on the applied methodology used to objectively quantify these movement dynamics and present the results with respect to the implementation of the solution-space dimensions. Finally, we will briefly discuss the results and propose a number of physiotherapeutic interventions aimed at optimizing the patient's use of her solution space.

Implementation

Method

On 3 January 2016, N., a 69-year-old woman, sustained a combined mild injury to her left knee and serious injury to her right knee during a fall while skiing. The diagnostic assessment showed that N. was in good health, with a mild sprain of her left knee and an anterior cruciate ligament rupture of her right knee, for which a conservative treatment and a brace were prescribed. On 15 February 2016, N. was referred for physiotherapy to promote an efficient, flexible, reliable, and powerful gait pattern.

The physiotherapist can evaluate the way a patient performs a task (activity level) by means of: (1) a subjective qualification or observational assessment and description; (2) a subjective quantification by translating relevant aspects of the observations to a Borg scale or visual analogue scale; and (3) an objective quantification by mathematically quantifying movement dynamics obtained by means of motion recording devices.

The initial subjective assessment of the way N. moved revealed an unequal bodyweight loading of the legs while rising from a chair, standing, and walking. From the RMC perspective, however, N. nevertheless displayed the motivation and ability to utilize her motor flexibility to attain the motor targets of getting up and moving forward, doing so slowly and cautiously, and notably only by exerting great effort to avoid discomfort or pain. Given her determination and capacity to utilize her motor flexibility, the goal of the therapeutic intervention was tentatively set at optimizing N.'s RMC during recovery in terms of attaining a flexible, reliable, and full-bodyweight loading of her legs during activities of daily living (ADLs), and to returning to playing golf as soon as possible. We therefore anticipated that, during the course of recovery, the vector in the solution space would display both a gradual shift towards a more similar movement behavior of both legs and a more automated movement control, which are both indicative of a transition toward gait normalization. N. consented to the report and treatment plan.

Subjective assessment of movement

4 March 2016: N. no longer wears the knee brace and relies mainly on a stiffness strategy (increased co-contraction combined with a decreased range of motion) to attain controlled bodyweight loading on her right knee.

6 April 2016: N.'s gait shows that bodyweight loading of the legs is more comparable, while movements are performed with more confidence even when distracted by the physiotherapist.

18 May 2016: N. no longer experiences any pain or discomfort when performing ADLs. Her gait pattern is well-balanced and executed with confidence, with each limb bearing full bodyweight. N. is, however, still hesitant getting into and out of a car, anxious not to twist her right knee. N. has returned to playing golf.

13 July 2016: Occasionally, N. has the sensation of her right knee "giving way". Having attained the main goals, N. and the physiotherapist jointly decide to end the treatment.

Objective quantification of movement dynamics

The task required the patient to walk straight ahead, uninterrupted and at a comfortable pace, on a flat surface in a well-lit room for a period of 20 seconds. To objectively quantify the behavioral observations, we made use of SoapSynergy, an affordable, low-end, stand-alone motion-recording system (Soapweer B.V., Zijderveld, Netherlands) that monitors and records movement in three directions along the *x, y*, and *z* axes by means of four miniature sensors (MTw, Xsens Technologies B.V., Enschede, The Netherlands). The sensors were placed on the body segments bordering the uninjured and injured knees (i.e. the ventral surfaces of both thighs midway between the hip and knee joints and the ventral surfaces of both lower legs midway between the knee and ankle joints). Based on mathematical functions, the computerized analysis of the kinematic recordings allows for an accurate quantification of the characteristic motion dynamics. Various dedicated software applications are available for use in rehabilitation settings to quantify motion dynamics. We used the SoapSynergy software application to calculate the relevant variables (see next paragraphs) from the recorded raw angular velocity data (deg/s) sampled at a rate of 100 Hz.

Information and control processes variable

Each movement is unique (unicity principle). Even repetitive movements are unique in their composition and performance or, as Bernstein (1967) puts it, are: “repetition without repetition”. Variability is an intrinsic property of all complex adaptive systems. Early theories on movement variability emphasize the underlying mechanism of noise in the neuromuscular system (Faisal, Selen, and Wolpert, 2008). Neuromotor noise is taken to be responsible for movement errors with respect to a target value or trajectory. Later views on movement variability propose that these fluctuations in movement signals also contain valuable information stemming from neuromotor processes evolving at the various system levels (Newell, Deutsch, Sosnoff, and Mayer-Kress, 2006). Movement signals can be mathematically transformed to the frequency domain (periodicity in Hz) using a Fourier transformation. By means of the “power spectral density” (PSD) function, we can then compute (analyze) the relative contributions of the periodicities of intrinsic variabilities in the generated movements associated with specific neuromotor control processes.

This analysis provides insight into the relative involvement of the various motor control processes, for instance by allowing the distinction of the extremely rapid myotatic reflex activity (i.e. physiological tremors) and the more slowly evolving visual and even slower cognitive monitoring processes. A particularly relevant PSD index for the solution space is the slope function (ß), which allows the quantification of the relative contributions of the different control processes in a particular motor pattern (Duarte and Zatsiorsky, 2001; Harrison and Stergiou, 2015). If ß is 0, this indicates that lower- and higher-frequency control processes have contributed equally to the production of the movement. A ß value < 0 reflects a systematic damping of the higher frequencies, denoting a relative decline in fast adaptive processes (e.g. physiological tremor, myotatic, or crossed reflexes) that contribute to movement execution. Accordingly, the smaller the negative value ß is, the stronger the contribution of the relatively slower control processes (e.g. visuomotor feedback) to the production of movement. In this article we use ß as a relative measure, that is, to indicate whether control processes were relatively slower or faster compared to previous measurements. Since ß as a relative measure is additive, we calculated the mean ß value of the three movement directions of each body segment. Next, we computed the absolute value of ß, subsequently denoted as |ß|. We used |ß| to facilitate reading, as higher absolute beta values represent more visual and cognitive control.

Time variable

Milestones can be used to mark specific points along the recovery timeline, which may signal anchors such as the start and end of the physiotherapeutic input or points in injury-specific protocols (e.g. the surgeon’s protocol), but also individually defined anchor points based on observational assessment. In many instances, milestones do not impact the duration of the recovery, but instead mark major progress points that must be reached to achieve the expected recovery. In the present case, we used the following four subjective progress assessments as anchor points: 4 March 2016, 6 April 2016, 18 May 2016, and 13 July 2016.

Degrees of freedom variable

More recently, attention has shifted from movement variability (motor fluctuations) to short- and long-term temporal dependencies in motion variability (i.e. structural variability) (Harbourne and Stergiou, 2009). A motion system is deemed rigid if the motor fluctuations hardly change over time, while it is considered flexible when short- and long-term motor fluctuations change markedly over time. Motor fluctuations that exhibit a certain degree of regularity can be associated with relatively predictable behavior, while motor fluctuations displaying a certain degree of irregularity are indicative of relatively unpredictable behavior.

Here, we apply the concept of entropy to capture the degree of regularity or predictability of movement behavior. In this article, we define entropy within the context of the motion system as the amount of information necessary to describe movement behavior. A high entropy value (e.g. large amount of information required) means that the neuromotor system can potentially generate many solutions to execute a movement successfully, thereby making the expected final movement outcome relatively more chance-dependent (i.e. less predictable). In contrast, a low entropy value (e.g. small amount of information required) is indicative of a potentially limited informational resource to generate solutions for successful movement execution resulting in a relatively more predicable final movement outcome. Consequently, higher entropy values indicate that the neuromotor system can utilize a larger number of compensation strategies to successfully adapt to changing or unpredictable circumstances, and vice versa.

In the present case study, the concept of entropy is applied to specify the current measure of regularity in the patient's motor system (SEn) (Harbourne and Stergiou, 2009). Highly regular movements will yield low SEn values, while highly irregular motions will have higher SEn values. Since entropy is additive, we applied the computed mean SEn of the three movement directions of each relevant body segment.

Results

Figure 2 displays the two-dimensional representations of the recovery paths in solution space of the thighs (left panel) and lower legs (right panel) of the uninjured (solid lines) and injured (dotted lines) legs. The left panel shows a nonlinear increase of automated control (|β| values) for both thigh motions over time and also that the movement regularity (SEn values) of both thighs becomes more comparable over time in a nonlinear fashion. The increase of automated movement control indicates that fast adaptive neuromotor processes become relatively less damped during the course of N.'s recovery (i.e. fast adaptive processes are relatively more involved in the movement generation of the thighs as recovery progresses). Concurrently, the movement regularities of the thighs become more comparable over time, indicating that they are increasingly described by the same amount of information (i.e. they compensate less for the motions executed by the other thigh). In sum, the solution space for the thigh segments as depicted in the left panel of Figure 2 shows a shift toward stronger automated movement control and a shift toward comparable movement regularity during the course of recovery.

In the right panel of Figure 2, the representations of the recovery paths in the solution space of the lower legs show a nonlinear shift towards stronger automated movement control; however, it does not reach the level of automation recorded for the thighs. Furthermore, we see a shift away from the comparable movement regularity, indicating a stronger compensation strategy over the course of recovery.

The changes in the representations of the recovery paths in the solution space dynamics of the injured and uninjured lower legs reflect the characteristic behavioral changes observed during motor rehabilitation (Fitts and Posner, 1967). During the initial stages of recovery, highly predictable, regular, visually controlled stiff movements often change into a more flexible, unpredictable and more explorative movement behavior. Subsequently, the mass-inertia characteristics of the limbs become exploited in order to regain an efficient, more cognitively monitored gait.

In Figure 3, the data from Figure 2 are rearranged to highlight the representations of the recovery paths in the solution space of the uninjured and injured legs. The figure accordingly displays two-dimensional

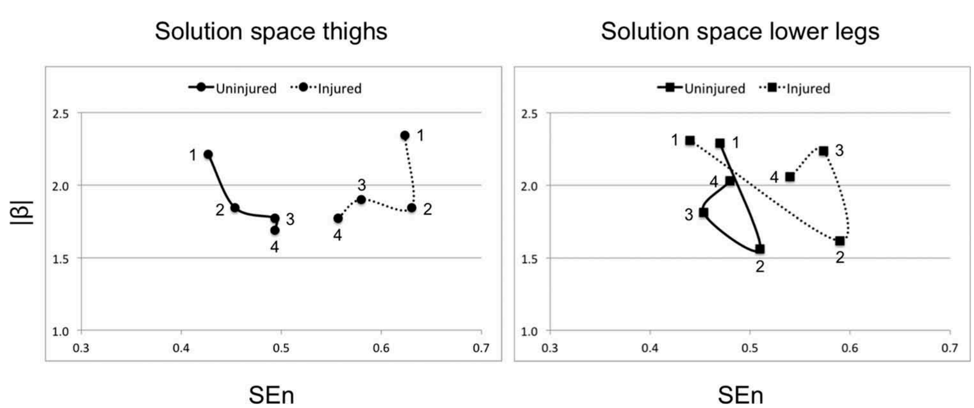

Figure 2. Two-dimensional representations of the recovery paths in the solution space of the thigh (left panel; closed circles) and lower leg motions (right panel; closed squares) of the uninjured (solid lines) and injured (dotted lines) legs. The data represent the "information and control processes" dimension (|β|) as a function of the "degrees of freedom" dimension (SEn) at four points in time (1, 2, 3, and 4) corresponding to the four recording dates (4 March 2016, 6 April 2016, 18 May 2016, and 13 July 2016, respectively).

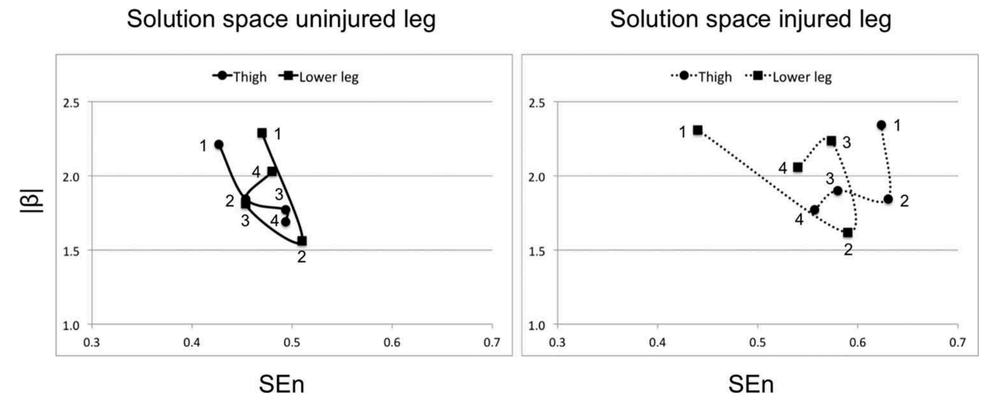

Figure 3. Two-dimensional representations of the recovery paths in solution space of the thigh and lower leg of the uninjured left leg (left panel; solid lines) and the injured right leg (right panel; dotted lines). The data represent the "information and control processes" dimension (|β|) as a function of the "degrees of freedom" dimension (SEn) at four points in time (1, 2, 3 and 4) corresponding to the four recording dates (04/03/2016, 06/04/2016, 18/05/2016 and 13/07/2016, respectively).

representations of the recovery paths in the solution space of the thigh and lower leg of the uninjured left leg (left panel; solid lines) and the injured right leg (right panel; dotted lines). Figure 4 depicts two rectangles that enclose the two-dimensional areas of the recovery paths representations in the solution space of the uninjured and injured legs.

Figure 3 shows that, for the representations of the recovery paths in both spaces, the movement regularity between the thighs and lower legs become relatively more comparable within each leg, compensating less for each other while showing an overall shift toward the stronger automation of movement control over time. Strikingly, during the recovery process, the representations of the recovery paths of the injured leg exploit a larger portion of the solution space than the uninjured leg (Figure 4). In this case, the ratio of the sizes of the rectangular areas (uninjured/injured) was 1:2.23.

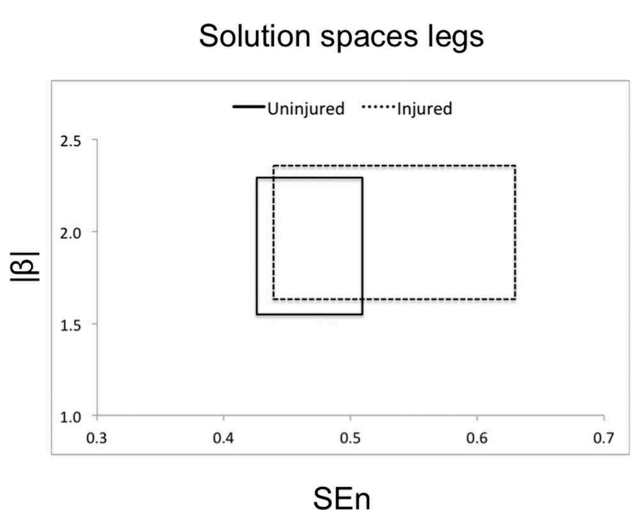

Figure 4. Visual representation of the two-dimensional areas of the solution space representing the recovery processes related to the uninjured left thigh and lower leg (solid border) and the injured right thigh and lower leg (dotted border). The solution space shows the "information and control processes" dimension (|β|) as a function of the "degrees of freedom" dimension (SEn).

Discussion

Here, we have introduced the concept of solution space as a tool to promote and monitor recovery after an injury to the musculoskeletal system, and presented the first results derived from a female patient. We have illustrated that, overall, the results of the solution space dynamics were in agreement with our expectations, in that they corresponded well with our successive subjective observations during the course of recovery. Even though adults have separate functional networks at their disposal to control walking and are able to train the circuits controlling the right and left legs individually, the legs are not insulated from the control of higher-level systems (Choi and Bastian, 2007). This is readily demonstrated by the mirrored trajectories of the recovery path representations in the solution spaces of the thigh segments (depicted in Figure 2, left panel) and the lower-leg segments (right panel) bordering the injured and uninjured knee. This means that, in this case, the solution-space dynamics representing recovery over time are controlled by higher-level systems, rather than the separate functional networks controlling leg motions underscoring the existence of compensatory mechanisms between the injured and uninjured knees. This observation is supported by previous studies showing that bilateral findings occur in unilateral injuries (Paterno et al., 2012; Salmon et al., 2005).

We have previously stated that movement variability hinges on the flexible organization of the neuromotor system. In this case, Figures 3 and 4 clearly show that the dynamics of motor recovery, as captured in the recovery path representations in the solution space of the injured leg, exploit a relatively larger space than that of the uninjured leg. The patient is apparently able to explore and exploit potential mechanisms in her motor system, thereby allowing sufficient variation in available movements with her injured leg. It seems plausible to state that motor-rehabilitation is served by intervention strategies that identify and modulate constraints on the movement system to facilitate movement variability instead of restricting it.

Physiotherapeutic interventions

To make optimal use of a patient's solution space, the physiotherapist needs to identify the most pertinent components of that space and take these as the starting point for the intervention. Advising the patient against using a stiffness strategy by reason of it being a suboptimal motor pattern may frustrate them and hinder their recovery. It is far more prudent to examine whether the patient is capable of flexibly adjusting the chosen strategy to changing task demands. The extent to which the patient can do so then reflects the potential options that can be exploited to foster recovery. The patient is also to be encouraged to keep exploring alternative motor options that may expedite the rehabilitation process. A suitable method to promote motor (re)learning is having the patient shift their bodyweight from one leg to the other on a rocking board, initially with the aid of a trapeze harness if required. This exercise allows the gradual, controlled reintroduction of degrees of freedom into the motor-coordination systems. The gentle loading of the knee joint and the soft swaying and tilting motions of the board will create a new sense of self-confidence, after which gradients and frequencies can be manipulated (amplified and varied) to improve muscle force, movement stability, and balance performance (Rutherford, 1988).

Facilitating and disrupting standing balance, stance transfers, and gait will further promote gait flexibility. Here, the varying perturbation conditions will impel the patient to swiftly adapt to the impending loss of balance, prompting a renewed reliance on the faster control mechanisms. Through leg dangling and swing exercises, the patient will relearn to exploit the mass-inertia characteristics of the lower limbs and hence regain an efficient gait. Recently, Roelofsen et al. (2016) showed that haptic tracking tasks (i.e. active, assisted movements) reduce the motion-planning challenges of moving the two feet at different amplitudes. Such active, guided movements based on externally induced haptic information may then prove especially valuable to help patients bypass the development of a bad habit. A slow walking pace facilitates a conscious, controlled motor pattern. When prompted to adopt a faster pace, the patient will be compelled to relearn to take advantage of the biophysical properties of the motor system (Shepherd and Carr, 1994), which will trigger a more even bodyweight loading on the legs and an efficient, flexible, reliable, and powerful gait pattern.

In closing

In rehabilitation, the focus is generally on predefined areas of care, including functional strength, mobility, physical functioning, activity level, and quality of life. Based on the model and results presented in this article, and as one of the core concepts of the solution space, we strongly recommend behavioral flexibility as a relevant focus for the physiotherapist. Arguably, a recovering motor system will show ample variation in movements that are indicative of adaptation processes and compensation strategies. This abundance of motor solutions therefore implies that the physiotherapist must always ensure that an increase in a patient's performance level does not compromise the motor variability of the neuromotor system.

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Declaration of interest

The authors report no conflicts of interest.

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