LOW-BACK PAIN PATIENTS LEARN TO ADAPT MOTOR BEHAVIOR WITH ADVERSE SECONDARY CONSEQUENCES

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short title: adaptive motor behavior in low-back pain

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ABSTRACT (limited to 40 to 60 words)
We hypothesize that changes in motor behavior with low-back pain are adaptations aimed at minimizing risk (real or potential) of further pain. Through reinforcement learning, pain results in more stereotypical motor behavior, leading to increased loading and impoverished sensory feedback, contributing to cortical reorganization and proprioceptive impairments leading to reduced ability to control lumbar movement in a robust manner.

SUMMARY (limited to 20 words)
We propose that reinforcement learning changes motor behavior in low-back pain to minimize risk (real or potential) of further pain.

KEY POINTS (limited to 5 points and 150 words)

- Low-back pain tends to change motor behavior towards increased co-contraction, reduced deep muscle activity and reduced within-subject variance.
- Minimizing a weighted sum of costs, including the risk of losing control and nociceptive input, predicts such changes with pain.
- In addition to actual benefits with respect to risk and nociception, changes may be driven by maximization of perceived benefits.
- Originally adaptive changes induced by such a pain-related learning process have negative consequences that may outweigh benefits in the long term.

KEY WORDS (5-7)
Low-back pain, reinforcement learning, nociception, postural control, motor control

INTRODUCTION

Low-back pain (LBP) is widely prevalent and the related functional limitations, limited effects of treatment, and frequent recurrence contribute to making LBP the leading cause of years lived with disability globally (15). Motor control exercise is a widely used treatment for LBP and although systematic reviews support its effectiveness, like other treatments for LBP, the effect size is not large (33). A better understanding of the nature of and mechanisms behind motor control changes in LBP should lead to better effects.

Motor control in LBP is changed at many levels of the nervous system. Studies of individuals with and without LBP have reported differences in voluntary trunk muscle activation (45), trunk muscle reflexes (32), trunk kinematics (20), and in cortical mapping of sensory inputs from (5) and motor outputs to (36) the trunk. However, the literature is far from consistent regarding the nature of these differences. For example, according to a systematic review, there is evidence of increased as well as decreased trunk muscle activation in LBP (45).

Here we propose a hypothesis on how LBP affects motor control, which may account for these inconsistencies. We hypothesize that changes in motor control with LBP reflect functional adaptations acquired through reinforcement learning (Figure 1). In reinforcement learning a reward (positive reinforcement) or the absence or reduction of a cost (negative reinforcement) increases the likelihood that a performed behavior will be repeated and thus be learned. In this context, movement-related pain may function as a negative reinforcement and the (sense of) being able to prevent pain provocation as a positive reinforcement. Motor control can be considered as the outcome of a learning process aimed at optimizing a combination costs and rewards. For clarity, either costs or rewards are usually inverted, such that a sum of weighted costs can be minimized or a sum of weighted rewards can be maximized. In pain-free conditions, costs associated with control efforts or muscle activation are considered most important. We assume that with LBP, weighting of costs associated with potential loss of control over posture and movement, and costs associated with potential pain provocation increase and one learns to minimize this new weighted sum of costs. Although the resulting muscle activation and movement patterns may differ between individuals, patients with LBP will tend to control posture and movement more rigidly, causing more stereotypical muscle activation and kinematics. Such adaptations entail higher muscle activity, higher compressive loading of the spine, and impoverished sensory feedback, i.e., less variability of the afferent signals, from the lumbar area. The latter would have the potential to contribute to neuroplastic changes in sensory

and motor regions of the cortex, and proprioceptive impairments leading to reduced ability to control lumbar movement in a robust manner. These secondary, long-term effects may contribute to recurrence and chronicity of back pain.

The hypothesis proposed thus consists of two parts: 1) LBP causes adaptive motor control changes through reinforcement learning, 2) these adaptations have potential negative long-term consequences. While an adaptive nature of motor control changes with LBP has been proposed in previous publications (e.g. 14,24,43,45), resulting predictions mainly regarded levels of muscle activation. Furthermore, these previous publications either assumed hard-wired reflexive changes in motor behavior with pain (24), or did not address the process underlying these changes (14,43,45). As will be detailed in the following, the notion that adaptations arise through reinforcement learning is important from a clinical perspective. For the second part of the hypothesis, previous publications have alluded to adverse side-effects of adaptations (14,45), but that this may contribute to reorganization of the sensory and motor cortex has to our knowledge not been discussed previously. We would like to emphasize that the ideas proposed here are likely applicable to other movement-related pain syndromes, but we will limit ourselves here to LBP, as this allows more specific testing of the hypotheses derived.

The aims of the present paper were to describe this hypothesis in more detail, to derive testable hypotheses and to confront such testable hypotheses with empirical findings from previously published studies. In the first part of the paper, we describe how LBP might induce a learning process leading to adapted motor behavior. We provide a formalization of this part of the hypothesis in a simple optimization model of trunk motor control, which yields predictions on motor behavior in patients with LBP that we compare with empirical findings. In the second part of the paper, we will describe how these changes on motor control may lead to adverse physiological and mechanical effects as well as neurological effects and how these secondary effects might play a role in persistence of LBP.

<< Figure 1 here >>

BY WHAT MECHANISM DOES LBP AFFECT MOTOR CONTROL?

Many studies have shown that normal motor control can be approximated by models that assume that the central nervous system (CNS) uses some form of optimal control, i.e. it achieves the task goal at a minimal cost. Examples of costs proposed in the literature are neural drive or muscle activation, required muscle force or associated metabolic costs, and

path length or jerk. In line with this assumption, pain-free subjects recruit trunk muscles in a manner that is consistent across individuals and compatible with minimization of dynamic costs (42). Experimentally induced nociception from back muscles and, or the resulting pain perception, changes control of trunk muscles in a manner resembling that observed in clinical LBP (9,45). Nociception may modify motor control on-line, by providing feedback regarding the consequence of the exerted control, possibly even in pain-free conditions. In addition, pain experience is likely to cause anticipatory changes in motor control (38), i.e. one would choose motor strategies that avoid pain provocation. We propose that control changes arising from nociception and pain can be understood in the context of optimal control.

Optimal control is generally thought to be the outcome of reinforcement learning. Efference copies of the motor commands and feedback on the consequences of the motor actions provide the individual with information on performance and associated costs, allowing adaptation of motor commands to achieve the task goal with minimal costs in terms of neural drive (control effort) or metabolic or mechanical costs of muscle force production. It has been suggested that planning of movement occurs sequentially at two hierarchical levels: first planning of the kinematic trajectory and subsequently planning of a muscle recruitment pattern that fits the planned kinematic trajectory (18).

In the present context, adaptation of motor control to changing conditions, in our case to the presence of nociception from the spine and the perception of LBP, is of particular interest. Many studies of reinforcement learning have addressed adaptation of control of goal-directed arm movements to mechanical perturbations. Such studies show that subjects gradually but consistently adapt to the mechanical perturbations, to converge on a near straight-line hand trajectory that closely resembles the unperturbed trajectory (18). Babic et al. (1) recently applied a similar paradigm to study adaptation of a squat movement to mechanical perturbations that could potentially lead to balance loss. The results differed in important ways from those in goal-directed arm movements. First, participants converged on an adapted center of mass trajectory after a relatively small number of trials. Second, although individual participants converged on a consistent trajectory, between-subject variance in the adapted trajectories was substantial. These differences were interpreted as reflecting that the CNS takes other costs into account in addition to costs of movement. Specifically, the risk of losing balance is non-trivial and obviously important in this task. Considering prevention of balance loss as an objective of the CNS, with a high weighting attached to it, predicts rapid convergence on an adapted trajectory (consistent with

experimental results), but this may represent a local minimum, because further exploration involves a steep increase in costs, or in other words comes at a risk of balance loss.

More generally, we suggest that motor control is the outcome of a learning process in which a weighted sum of costs is minimized. The weighted sum comprises costs related to control effort and muscle activity such as neural drive, metabolic costs and fatigue development, but also of costs that reflect more indirect effects of the selected motor pattern, such as the risk of losing control over posture or movement and the possibility of pain provocation. In an individual in pain, the latter two costs would be expected to receive higher weighting than in a pain-free individual.

A model of motor control changes with LBP

We here use the selection of a muscle recruitment strategy given a specific, static kinematic situation of the trunk as a simplified model of motor control changes with LBP. We simulate a simple muscle-joint system, representing the trunk, with one degree of freedom, controlled by two extensor muscles and one antagonistic flexor muscles (Figure 2). The task performed requires production of a given net moment (20 Nm) by these three muscles, which is comparable to standing with a slightly forward inclined trunk.

We assumed that three costs govern the selection of a muscle recruitment pattern. The first cost is to minimize the neural drive, modelled as:

$$C_1 = \sum_{i=1}^{n} A_i^p,$$

with *A* a vector of n (here 3) levels of muscle activation. The value of the exponent *p* was set to 3, in line with minimization of muscle fatigue, which has been shown to accurately predict muscle activity of trunk muscles (42) (reasonable predictions were generated with any $p > 1$). The second cost is trunk admittance, i.e., the objective is to maximize the resistance against perturbations. In reality, this will be achieved by a combination of co-contraction and increasing of feedback gains (47). In this simplified model, this can only be achieved through increasing muscle stiffness by means of co-contraction. Effects of muscle contraction on joint stiffness can be modeled as a function of muscle force, muscle length and muscle moment arm (31), which yields as a cost function:

$$C_2 = 1/\sum_{i=1}^{n}(F_i\, d_i^2/l_i),$$

with *F* the vector of muscle forces calculated as $A * F_{max}'$, *d* the vector of muscle moment arms and *l* the vector of muscle lengths. The third objective function is to minimize nociceptive afference. Obviously, this can be modeled in many different ways, based on assumptions of what structures and which type of loading induces nociceptive input. We

used the simple assumption that nociception increases with the total muscle force produced, yielding:

$$C_3 = (\sum_{i=1}^{n} F_i)^p ,$$

We arbitrarily set *p* to 1. But results presented below held over a range of values for *p* from 0.5 to 10.

The three cost functions were normalized to their maximum over the range from no to full activation for all muscles, to assure equal scaling over the range of muscle activation from 0 to 1. The costs as functions of the forces in the two extensor muscles are illustrated in the top panels of Figure 2. Costs 1 and 3 penalize high muscle forces, whereas cost 2 penalizes very low muscle forces. The resulting cost function is a weighted sum of all three scaled cost functions:

$$\sum_{j=1}^{3} w_j C_j ,$$

with *w* the vector of weight factors and by definition $\sum_{j=1}^{3} w_j = 1$. This weighted cost function is minimized subject to the constraint:

$$M_{net} = -\sum_{i=1}^{n} F_i d_i ,$$

ensuring that the three muscle together produce a net moment (M_{net}) of 20 Nm.

We explored the effects of changing the vector *w*, to simulate the effects of LBP. The initial setting for the pain-free condition was *w(0)* = [.9975,.0025,0] i.e. no objective to minimize nociception and only a low weighting of admittance, which was selected to obtain a realistic level of antagonistic muscle activity. For the pain condition weighting factors were set to *w(1)* = [.8,.1,.1], implying a substantial penalty on admittance and nociception.

The lower panels in Figure 2 illustrate the cost function as a function of load sharing between the two synergistic extensor muscles. Reinforcement learning takes place through variation of muscle forces and observing changes in the costs, i.e. by exploration of the surface of the weighted cost function, through which one would finally converge on the optimal recruitment pattern, i.e. the combination of muscle forces with the lowest cost, indicated by an asterisk.

Model predictions

As can be seen in Figure 2, changing the weights in the weighted cost function from *w(0)* to *w(1)* shifts the optimal muscle recruitment pattern towards higher activation of the larger of the two extensor muscles, due to the higher weighting of admittance, which favors the muscle with the larger moment arm. In addition, the level of antagonistic co-contraction increases. Furthermore, the curvature of the surface of the weighted cost function around

the optimum solution is steeper for *w(1)* than for *w(0).* The model results thus predict higher co-contraction, preferential recruitment of large superficial muscles and less exploration with pain than in the pain-free condition. Of note is that the same model would predict less obvious qualitative changes in muscle activity when higher net moments are produced. This is because the second cost function, limiting admittance, affects muscle recruitment mainly at low levels of muscle activity, while the third cost function, to limit nociception, penalizes high muscle activity, which the first cost function also does. It should be noted that the present cost function for pain is quite simplistic. In reality, it could be that activity of one muscle provokes pain and that of another muscle does not. This would require another formalization of the cost function to minimize nociception. However, such a cost function is unlikely to be generic, the painful muscle may be a different one in different patients. Therefore, for the present purpose we choose this very simple cost function.

An important aspect of the proposed hypothesis is that minimization is based on reinforcement learning. This implies that costs taken into account can reflect perceptions rather than direct information from sensory feedback or efference copies. Important in this context, pain perception is not simply a function of nociceptive input. While nociceptive afference may lead to perception of pain, the presence, intensity and nature of this perception are shaped by cognitive factors, among which the expectations that the individual has about pain (4). The objective may be to minimize this pain perception instead of the nociceptive input, or to maximize perceived safety rather than actual robustness of the motor strategy. This introduces the possibility for a feedback mechanism, where the very fact that one changes the motor strategy leads to a perception of increased safety or decreased pain perception. This could reinforce the strategy choice, despite the possibility that the perception could be unrelated to effects of the movement strategy on actual safety or nociception. This may explain why increasing muscle activity can reduce pain perceived under a constant nociceptive input (19). We have recently provided more specific data to this effect; when participants were provided with a noxious stimulus during wrist movement, adaptation of the motor strategy led to reduced pain perception regardless of whether the noxious input was reduced by the adaptation (Bergin, Tucker and Hodges, 2016 unpublished data).

It is important to note that the proposed model does not predict local minima of the weighted sum of costs. Nevertheless, the curvature of the objective function for the condition with pain suggests that individuals might end up using sub-optimal solutions, since exploration starting from any near optimal point is heavily penalized with changes of the

recruitment pattern in most directions. Local minima will occur when one of the objective functions is non-convex. This may occur for pain-related objective functions in kinematic planning, as pain often changes non-monotonically with trunk angle, a so-called painful arc (2). It may also occur when a cost function varies with activity of certain muscles only, which as discussed above could be the case for nociception.

<< Figure 2 here >>

CHANGES IN MOTOR BEHAVIOR WITH LBP

The proposed reinforcement learning model described above predicts that patients with LBP will display: 1) higher co-contraction, 2) more activity of large superficial muscles and 3) lower variability in muscle recruitment than pain-free individuals. In addition, it predicts that; 4) such pain-related changes will be affected not only by nociception but also by pain-related cognitions, such as fear or anticipation of pain, which would change weighting of the objectives similarly to nociception. Finally, the theory suggests that with pain subjects may end up in local minima which would imply that: 5) between-subject variability in motor strategies may be larger among patients with LBP than among pain-free individuals. The following sections review the evidence that clinical LBP and experimental noxious stimuli to the low back are associated with changes in motor behavior in-line with these predictions.

Co-contraction

The model predicts that co-contraction increases during pain to reduce admittance. Such a response has been observed in healthy subjects when task conditions are perceived to potentially threaten control of trunk movement (44). A pain-related increase in co-contraction would be expected also in low-demanding tasks such as maintenance of unloaded upright posture, since intrinsic stiffness of the trunk is minimal in such conditions (3). No feedback control was implemented in the model, but a high weighting of an objective to minimize admittance with pain would also predict an increase in feedback gains (47). Kinematically, these changes in muscle recruitment would be associated with small displacements after mechanical perturbations. In line with the model predictions, experiments using experimental noxious stimuli to the low back have shown increased activity of trunk muscles and decreased displacements after trunk perturbations (8). Also studies comparing participants with and without LBP have commonly reported increased

activity of trunk muscles, particularly in low-intensity activities (45), as proposed by the model. Moreover, smaller displacements after perturbations have been found in participants with LBP (7,17).

Preferential recruitment of superficial muscles

The model predicts that pain biases recruitment towards superficial muscles with large moment arms relative to deep muscles with smaller moment arms. This prediction is supported by studies on anticipatory activation of trunk muscles in association with perturbations of trunk posture caused by rapid movements of the upper and lower limbs. These studies have reported reduced and delayed activation of deep muscles relative to superficial muscles after administration of a noxious stimulus to the low back (10). Also studies comparing participants with and without LBP have consistently reported delayed recruitment of deep muscles relative to superficial muscles (9,11-13,25,28) and earlier activation of the superficial abdominal muscles in participants with LBP (30).

Within-subject variability

The higher weighting of objectives related to admittance and nociception caused the surface of the weighted cost function to be more curved, which would suggest that exploration is limited by pain. This prediction was supported in a recent study where we applied a force field to the ankle during gait, and provided noxious input to the tibialis anterior muscle. Participants with and without pain adapted quickly to the force field to continue walking without loss of balance, but only the pain-free participants were able to continue to refine the strategy over time; participants in the pain group continued to use the initially adopted solution (Bouffard, Salomoni, Mercier, Tucker, Roy, van den Hoorn, Hodges, Bouyer, 2016 unpublished data). The limited exploration would lead to a reduced within-subject variance of trunk muscle recruitment and trunk kinematics. Both reduced variance of muscle recruitment patterns after administration of a noxious stimulus to the low back (e.g. 40) and increased variance have been reported (21). Note that our hypothesis would predict an initial increase in variability in response to incident pain, as this acutely changes movement-related costs, followed by a reduced variability as a result of the steeper increase in the weighted sum of costs with pain. This is in line with differences observed between effects of experimentally induced acute pain and chronic pain in the neck and shoulder region on movement variability (26). Patients with chronic LBP have been reported to display lower variability of muscle recruitment (6,16) and lower variability of trunk

kinematics (22,29) than pain free controls, but opposite findings have also been reported (22,49).

Effect of pain-related cognitions

In-line with our hypothesis, effects of LBP on trunk muscle activity (41) and trunk displacement after perturbations (17) are more pronounced in participants with high scores on pain catastrophizing or fear of movement. Similarly, delayed deep muscle activation was more pronounced in participants with high fear of pain (39) and variability was more decreased in participants with negative pain-related cognitions (6) and persisted after pain had resolved only in these participants (30).

Between-subject variability

Although not a prediction of our model, the general hypothesis suggests that different individuals may end up using different motor strategies after the development of LBP, because they will not find the optimum solution as a consequence of limited exploration. Formal comparisons of between-subject variability between groups with LBP and pain-free groups are lacking, but one systematic review concluded that between-subject variability of trunk kinematics is indeed larger among study populations with LBP than among those without LBP (20).

Conclusions regarding motor behavior in LBP

The model used to illustrate the hypothesis that changes in motor behavior with LBP are determined by reinforcement learning, which minimizes uncertainty and pain, is obviously simplified. Most importantly nociceptive inputs or pain experiences may shape the objective function for avoiding pain in a much more complicated way than represented here. In spite of this, empirical observations are consistent with predictions overall. Inconsistency of findings with respect to within-subject variability may be related to the fact that LBP also interferes with motor control, e.g. through impaired proprioception (50), or pain-related inhibition (e.g. 25). Consequently, the variance observed may be the net effect of opposing effects of pain interference and adaptations resulting from reinforcement learning. Moreover, pain-related cognitions moderate the effects of LBP on motor behavior (as proposed by the model), which leads to variance in effects between individuals and between conditions. For instance, adaptive motor behavior may be more obvious in tasks that impose substantial threat of pain.

CONSEQUENCES OF CHANGES IN MOTOR BEHAVIOR WITH LBP

While adaptive and with short term/immediate benefit, in the longer term, changes in trunk motor control with LBP may have adverse mechanical, physiological and neurological consequences that may outweigh the benefits. Increased and more sustained trunk muscle activity would come at a cost in terms of muscle and spine loading. Trunk extensor contractions at intensities below 5% of maximum activation cause fatigue development within half an hour, if variability of activation is low (46). Patients maintaining sustained trunk muscle activity, even at a low level, may thus incur muscle fatigue and related discomfort, or even pain of muscular origin (48), especially in the presence of sensitization. Increased trunk muscle activation to reduce admittance also comes at the cost of increased spinal loading. LBP patients have been shown to expose their spine to higher forces during lifting than healthy subjects due to co-contraction (e.g. 27). Furthermore, low-level co-contraction of trunk muscles may occur in LBP patients even at rest (45), implying sustained compression of the spine, which animal models implicate as a cause of intervertebral disc degeneration (23). There may also be adverse mechanical consequences of the decreased variation that would be expected to accompany LBP. It is increasingly recognized that some degree of variation in tissue mechanical loading is essential for tissue health (34).

In addition to mechanical consequences, trunk control adaptations with LBP can be expected to have neurological consequences. Reduced variability in posture and movement likely yields impoverished afferent feedback and we hypothesize that this may contribute to the changes in representations of the trunk in the somatosensory (37) cortex observed with LBP. In turn, these changes in the sensory cortex could contribute to the impaired proprioception (35) and the related imprecision in control of trunk movement in patients with chronic LBP (50). Furthermore, stereotypical muscle recruitment patterns, with relative inhibition of deep muscle activity, is associated with changes in representations of trunk muscles on the motor cortex in LBP patients (5). These brain changes, in addition to the reduced motor variability (30), may limit the ability to re-learn normal motor control even after LBP has receded. It should be noted that reduced proprioceptive information might strengthen the reinforcement learning process induced by LBP as a consequence of increased uncertainty of the outcomes of motor commands and consequently increasing perceived threat.

CONCLUSION

To further test the hypothesis that motor behavior changes with LBP are the result of a reinforcement learning process in which potential loss of control over posture and movement and provocation of pain are minimized, several avenues of research could be explored. Manipulation of nociception and pain as a function of motor behavior can be used to shape objective functions and as such test the hypothesis that strategies to avoid the painful stimulus develop through exploration and reinforcement. Furthermore, as the review of literature provided above illustrates, the predictions of our model that within-subject variance of trunk motor behavior is smaller in patients with LBP than in pain-free controls needs further study, as does the prediction that between-subject variance is higher among patients with LBP.

The hypothesis proposed, specifically the potential for changes in motor behavior to underpin adverse secondary effects, indicates that interventions targeting these changes may be needed in spite of their initially adaptive nature. Furthermore, the hypothesis and data presented suggest that motor control exercise should be aimed at aspects such as increasing admittance, inhibition of superficial and stimulation of deep muscles, training of proprioception, and/or regaining confidence in the ability to control lumbar motion. Finally, in designing motor control interventions one needs to consider the potential for a reduced ability to (re-)learn 'normal' motor control due to the presence of pain and the secondary effects thereof.

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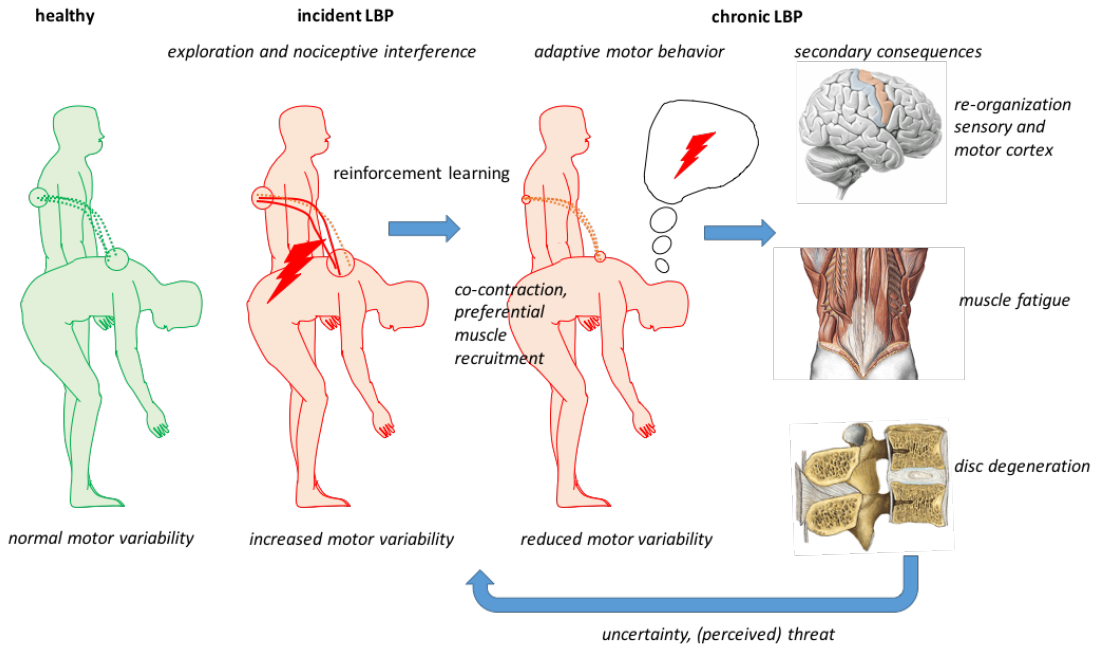

Figure 1. Schematic illustration of the hypothesis on motor control changes with low-back pain (LBP). In normal conditions, motor behavior is somewhat variable because many near-optimal solutions can be used to achieve the task goal. This is illustrated on the left, with the dotted lines representing near optimal movement trajectories of a marker on the trunk and the circles representing the area of endpoint positions of this marker over a series of repeated movements. With incidence of LBP, variability will increase because nociception interferes with motor control and because the subject will learn an adapted motor pattern with negative reinforcement by nociception, pain perception and positive reinforcement by the sense of having control over movement. Once the new optimal pattern (dashed line) is found, motor variability is reduced, since costs of movement (pain, potential loss of control) may rapidly increase with changes in behavior. The adapted motor behavior furthermore consists of increased levels of antagonistic contraction and preferential recruitment of muscles with large moment arms. This adaptive behavior may lead to secondary consequences in joint structures and muscles due to increased and more sustained muscle activity and to reorganization of the sensory and motor cortex due to the more stereotypical sensory feedback and selective muscle recruitment. These changes may increase uncertainty about motor control and hence perceived movement-related threats, which may further reinforce the adaptations in motor behavior.

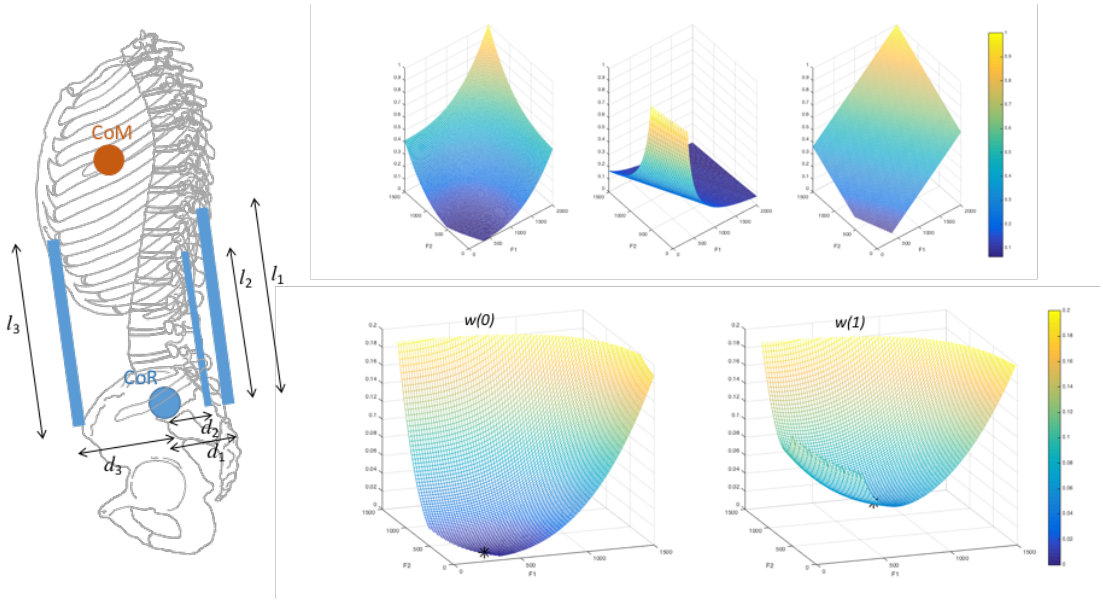

Figure 2. The left figure illustrates the model, with muscles represented by thick blue lines and muscle lengths (l_i) and moment arms (d_i) indicated by arrows. The upper body center of mass (CoM) is indicated by the red circle, the joint center of rotation (CoR) by the blue circle, with the inclination of the upper body leading to an external moment around the CoR of 20 Nm. The right graphs show in the upper panels the three objectives outlined in the text as a function of forces produced by muscles 1 and 2. For any combination of muscle forces in these diagrams, i.e. any position on the x-y plane, the force in muscle 3 is determined given the constraint function, which requires the three muscles combined to produce and internal moment of -20 Nm. The lower panels illustrate the weighted sum of the three objectives for weight vectors specified in the text, with the pain-free condition (*w(0)*) on the left and the pain condition (*w(1)*) on the right. The * indicates the optimum combination of muscle forces for each objective function.