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Review article

Possible changes in energy-minimizer mechanisms of locomotion due to chronic low back pain - a literature review

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ABSTRACT

One goal of the locomotion is to move the body in the space at the most economical way possible. However, little is known about the mechanical and energetic aspects of locomotion that are affected by low back pain. And in case of occurring some damage, little is known about how the mechanical and energetic characteristics of the locomotion are manifested in functional activities, especially with respect to the energy-minimizer mechanisms during locomotion. This study aimed: a) to describe the main energy-minimizer mechanisms of locomotion; b) to check if there are signs of damage on the mechanical and energetic characteristics of the locomotion due to chronic low back pain (CLBP) which may endanger the energy-minimizer mechanisms. This study is characterized as a narrative literature review. The main theory that explains the minimization of energy expenditure during the locomotion is the inverted pendulum mechanism, by which the energy-minimizer mechanism converts kinetic energy into potential energy of the center of mass and vice-versa during the step. This mechanism is strongly influenced by spatio-temporal gait (locomotion) parameters such as step length and preferred walking speed, which, in turn, may be severely altered in patients with chronic low back pain. However, much remains to be understood about the effects of chronic low back pain on the individual's ability to practice an economic locomotion, because functional impairment may compromise the mechanical and energetic characteristics of this type of gait, making it more costly. Thus, there are indications that such changes may compromise the functional energy-minimizer mechanisms.

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Possíveis alterações no mecanismo minimizador de energia da caminhada em decorrência da dor lombar crônica - revisão de literatura

Palavras-chave:
Dor lombar
Locomoção humana
Caminhada
Biomecânica
Consumo de energia

RESUMO

Um dos objetivos da marcha é deslocar o corpo no espaço da forma mais econômica possível. Porém, pouco se sabe como os aspectos mecânicos e energéticos da caminhada são afetados pela dor lombar. Ainda, caso haja prejuízos, é pequeno o conhecimento de como as características mecânicas e energéticas da caminhada se manifestam nas atividades funcionais, principalmente nos mecanismos minimizadores de energia da locomoção. Este estudo teve por objetivos: a) descrever os principais mecanismos minimizadores de energia da locomoção; e b) verificar se há indicativos de prejuízos nas características mecânicas e energéticas da caminhada decorrentes da dor lombar crônica (DLC) que possam comprometer os mecanismos minimizadores. Estudo caracterizado como revisão narrativa de literatura. A principal teoria que explica a minimização do dispêndio energético durante a caminhada é a do pêndulo invertido pelo qual o mecanismo minimizador converte energia cinética em energia potencial do centro de massa e vice-versa durante a passada. Esse mecanismo é fortemente influenciado por parâmetros espaços-temporais da marcha, tais como comprimento de passo e velocidade preferida da caminhada, que, por sua vez, podem estar severamente alterados em pacientes com dor lombar crônica. Contudo ainda há muito que se entender sobre os efeitos da dor lombar crônica sobre a capacidade do indivíduo de praticar uma marcha econômica, pois os prejuízos funcionais podem comprometer características mecânicas e energéticas dessa modalidade de marcha e torná-la mais dispendiosa. Desta forma, há indicativos de que tais mudanças funcionais possam comprometer os mecanismos minimizadores de energia.

Introduction

The adoption of locomotion on two legs as an exclusive form of march was an important marker of human evolution, and energy saving, in this type of locomotion, is one of the main reasons for the establishment of bipedalism.[1–3] However, the bipedal locomotion cannot always be considered as a simple task. The trunk, essentially unstable for its multijoint characteristics, maintains its stability by muscular action that constantly modifies itself to ensure the needed posture to movements.[4] Therefore, the ability of locomotion depends on a complex interaction of patterns of coordinated movements of the hip, pelvis and lumbar spine, which, when harmonic, determine the normal biomechan-ical gait pattern.[1,5]

Walking is a form of locomotion that stands out by influencing multiple aspects in the physical, social and evolutionary spheres of human existence.[6] An anthropological and evolutionary vision makes us think that, if the modern man can walk quietly and use this ability to perform his daily activities, in the past perhaps this was not so simple for our ancestors - probably bipedal locomotion was used for escape, producing tiredness and fatigue. Bipedal locomotion was used to permit man's flight, causing greater exhaustion and fatigue. Throughout the evolutionary period, certain anatomical changes were occurring slowly over thousands of years, to allow the fixation of this mode of march and promoting adaptations of human locomotor system that provide us with perspectives on musculoskeletal disorders found in the current clinical scenario.[7]

The biped march encompasses many aspects that go beyond a simple act of placing one leg in front of the other. It can be understood as a cyclic movement with loss and recovery of the balance, due to the constant change of position of the body center of mass promoting body instability. Such instability is compensated by leg movements, ranging from a stance phase, which can be single-leg or bipedal, and a swing phase, in which the leg is free in the air. Thus, at the end of the swing phase, the center of mass lies in a posterior relation to the anteriorly extended leg and begins to rise, due to the kinetic energy, at the beginning of the stance phase, after the heel contact with the ground (i.e., heel-strike). During the first half of the step, the kinetic energy decreases as the center of mass gains height, with consequent increase of potential energy which reaches its peak in the middle of the one-leg support phase. In the second half of the step, the opposite occurs; the center of mass loses height and the potential energy is converted into kinetic energy. The reconversion between the mechanical energies connected to the center of mass during walking plays a crucial role in the individual's ability to walk as economically as possible, and is influenced by a number of spatio-temporal gait variables, such as step length and gait speed.[8–11]

The impairment of the normal gait cycle and the loss of characteristics of energy conservation between trunk and limb movements result in greater energy expenditure. Patients with diseases that compromise the ability to walk tend to develop compensatory gait patterns to minimize the additional energy expenditure.[9]

Low back pain is a common syndrome worldwide, generating relevant socioeconomic costs. According to estimates, 80% of people will experience an episode of this kind of pain at some point in their life. Low back disorders are multifactorial; and pathologic, physical, neurophysiological, psychological and social factors have a different impact on each individual, and in about 90% of cases it is not possible to pinpoint the cause of the dysfunction, which characterizes the non-specific low back pain picture. Despite the limitations to establish the relationship among clinical characteristics and the conditions causing low back pain with the effectiveness of treatment procedures, it is observed that biomechanical and physiological losses tend to follow chronic cases of low back pain. Many of these losses are identified in the literature, such as decreased speed of a comfortable gait, decreased step length and swing time,[12,13] decreased maximal aerobic capacity,[14] decreased resistance of the lumbar extensors with consequent anterior displacement of the center of mass, poor postural control,[15,16] incoordination of the pelvic and thoracic rotations,[17] delay in the planned activation of the transversus abdominis, and impaired relaxation phenomenon during trunk anteflexion.[18,19]

In a study that identified the main activities performed with difficulty in the perception of patients with chronic low back pain, it was observed that 56% of 101 volunteers reported low tolerance to walking as one of the five activities more poorly performed, this being the most prevalent item in that sample.[20] However, our knowledge it is still limited about how the mechanical and energetic aspects of locomotion, especially with respect to gait, are affected by low back pain and how the damages resulting from its occurrence are manifested in functional activities, mainly with regard to the energy-minimizer mechanisms of locomotion. The understanding of these issues would be an improvement to explain if the changes observed during walking in this population are due to the inability of the body to provide an economical gait, or if they exist precisely to preserve these energy-minimizer mechanisms.

Thus, this study aimed: a) to describe the main energy-minimizer mechanisms of locomotion; b) to check if there are signs of damage for mechanical and energetic characteristics of gait due to chronic low back pain, which may endanger the energy-minimizer mechanisms.

Method

This study was characterized as a narrative review of literature. We conducted a literature search in electronic databases: Capes, PubMed and SciELO articles, written in English, Portuguese and Spanish languages, listed from the intersection of the following keywords in English (low back pain, human locomotion, walking, biomechanics, gait, energy consumption) and their equivalents in Portuguese idiom (*dor lombar; locomoção humana; caminhada, biomecânica, marcha, consumo de energia*) in a search period delimited from 1998 to March 2013; as well as classic articles related to the subject, cited in the references of those previously selected articles.

Energy-minimizer mechanisms of human locomotion

The normal human gait can be defined as the march modality that humans use to move at low speeds. The gait cycle can be understood as the time period between two identical events in the walking process, and this full cycle is divided into two phases: stance and swing phases.[21]

The stance phase begins with the first contact of a foot (usually the heel) with the ground, ending with the last contact of the same foot with the ground, corresponding to hallux take-off. The swing phase begins with the last contact of the foot with the ground, ending with the first contralateral foot contact with the ground. During the first half of the stance phase, there is a decrease in the velocity of the center of mass until the midpoint is reached; on the other hand, in the second half the center of mass increases its speed again. During the stance phase, the leg remains extended and the midpoint of this phase coincides with the highest point of the trajectory of the center of mass.[8–10]

Complex phenomena, such as gait, in which many variables contribute to their occurrence (some of them difficult to quantify), may not always be amenable to studies in real conditions. However, in some fields such as biomechanics, these phenomena are simplified in the form of models, which can be mathematical, physical or conceptual ones; and such models allow us to understand the phenomenon more broadly.[22,23]

Although contradictory, there are two theories (models) reported in studies with respect to march that seek to explain the mechanisms by which this phenomenon can be more economical: the theory of six determinants of gait and the theory of inverted pendulum. The main difference between the two theories resides in the trajectory of the center of mass.[23]

The less accepted is the theory of six determinants, which proposes that a set of kinematic features, such as knee flexion at the time of stance and pelvic rotations, among others, are used strategically to permit that the center of mass of the body describe a straight trajectory during walking. The argument for such behavior is that the vertical oscillations of the center of mass generate an additional energy expenditure, due to the need for muscle contraction to speed it up and lift it against gravity. The main criticism of this model is that, to minimize the energy expenditure associated with the oscillations of the center of mass, it creates a need for the legs remaining bent in the most part of the step, and that this has more costly energetic consequences, in comparison with the oscillations of the center of mass.[23]

On the other hand, the theory of inverted pendulum is the more accepted, being used in the studies. The human march, on level ground and under a biomechanical perspective, resembles a “rolling egg” or an inverted pendulum; these analogies describe the behavior of the energy changes related to the center of mass of the body. Mechanical models that represent the behavior of the body center of mass, understood as the external work done to raise/lover and accelerate/delay the center of mass in relation to the environment, have been used to explain how each type of gait employs and saves mechanical energy. According to the inverted pendulum model (that can also be seen as a rigid segment model), when applied to gait, the kinetic and potential energies change in terms of phase opposition (while one of them reaches a minimum value, the other reaches a maximum value) during contact with the ground in the unipodal phase, allowing an interchange between the two energies. This model proposes that the mass center describes a curvilinear trajectory during the step (similar to a pendulum positioned upside down) and that the lower limb that supports the weight behaves as a rigid segment. In addition, this mechanism of energy fluctuation reduces the mechanical work imposed by the muscular system, thanks to the energy conservation; and this reduction is proportional to the body's ability to reconvert one energy type into another (i.e., kinetic energy into potential energy, and vice-versa) – a mechanical feature known as recovery.[8,10,24,25]

Thus, the act of walking with the knee extended in the stance phase appears to result in two advantages: in addition to providing the vertical displacement of the center of mass, facilitating energy conservation through exchanges between kinetic and potential energy, also allows that the action line (vector) of the body weight pass near the lower limb joints, so that there is little need for muscle action to prevent that these joints suffer from their imposed loads. These two conditions favor energy conservation.[26]

The pendulum transduction between kinetic and potential energies reduces the expenditure of chemical energy from both the positive muscle work (that required to increase potential and kinetic energy) and negative muscle work (that required to reduce potential and kinetic energy). The fraction of reconverted mechanical energy due to pendular transduction (recovery – %R) is defined mathematically as: $\%R = 100\ (W^+_f + W^+_v - W^+_{ext})\ /\ (W^+_f + W^+_v)$ where W^+_f is the positive work calculated from the sum, throughout the step cycle, of the positive increments promoted by the previous displacement due to horizontal kinetic energy ($CE_h = 0{,}5\ MV_h^2$, where M = mass of the body and V_h = the instantaneous horizontal velocity of the center of mass); W^+_v represents the positive work calculated from the sum, throughout the step cycle, of the positive increments promoted by the vertical displacement due to gravitational potential energy (PE = Mgh, where M = body mass, g = the acceleration due to gravity and h = the instantaneous height of the center of mass); + W ext is the positive external work calculated from the sum, throughout the step cycle, of the positive increments promoted by the total mechanical energy of the center of mass ($Em_{tot} = PE + CE_h + CE_v$, where PE = potential energy, CE_h = horizontal kinetic energy, and CE_v = vertical kinetic energy). CE_v ($CE_v = 0{,}5\ MV_v^2$, where M_v = instantaneous vertical speed) has been neglected in this calculation, because it does not influence W^+_v, since the vertical velocity is zero at the top and at the valley of the potential energy curve. Thus, the recovery represents the maximum fraction of positive energy increments linked to the center of mass that are reconverted by the pendulum mechanism throughout the step cycle.[10,27]

In an ideal pendulum, the energy exchange is complete (energy recovery = 100%). Nevertheless, in the human gait, the energy recovery is moderately high (up to 60%) and depends on the step length and walking speed. Recent literature suggests some contribution of elastic energy to the march mechanisms, by storing this energy and its releasing in the Achilles tendon and possibly through the arch of the foot. The participation of elastic energy during gait is accepted by some authors, although this kind of energy has an apparently more decisive participation in the race activity.[10,28,29]

During the locomotion, the gait parameters are adjusted so that the force, work, power and/or energy expenditure are minimized. Thus, during gait the average mechanical power is minimal, when the subject is walking on a step frequency close to that freely chosen (self-selected speed). Correspondingly, the oxygen consumption is also minimized at the same frequency.[30]

Under normal conditions, the power consumption of gait (metabolic power – consumption of oxygen per kilogram of body weight during a given time) is related to the intensity of effort, and can be affected by changes in speed. Thus, speed is a crucial measure, being determinant to energy expenditure in walking tests. The influence of speed is so relevant to energy consumption that the oxygen cost per meter walked (a concept called the transportation cost) is obtained by the ratio between metabolic power and speed of walking, being indicative of the quality of the walk.[9,31]

Transportation cost is a measure of the economy of locomotion and represents the amount of metabolic energy consumed to move one kilogram of body mass per unit of distance, being expressed as $J.kg^{-1}.m^{-1}$ [10,32] and provides a metabolic information of gait quality. Put more simply, transportation cost can be defined as the force required to move a unit of mass by a unit of distance.

The transportation cost varies depending on the speed with which the march is held, being usually lower in self-selected speeds for each gait type. Based on this, Margaria, in the late 1930s, proposed that the curves of transportation cost in terms of speed took the form of "U", because the farther the studied speed with respect to that self-selected speed, the greater the transportation cost.[10,33] In fact, the optimal walking speed has been defined in some studies as that speed in which, simultaneously, there is optimization of the contribution of mechanical parameters characteristic of this type of gait and a lower metabolic cost.[34]

walking at higher speeds than the self-selected one requires an increase in the activity of those muscles involved in propelling the body forward, being also associated with a greater step length, which increases the activity both of the muscles that contribute to leg swing as of those that contribute to the vertical control, since the vertical excursion of the center of mass of the body also increases. Conversely, walking at lower speeds becomes mechanically less efficient, because there is greater need for stabilization, and one can rely less on the elastic energy of the muscle and tendon units.[35]

Consequently, one might think that there is a parallelism between energetic and mechanic aspects of human locomotion. However, because of its complexity, many factors must be taken into consideration. Taylor and Heglund[36] showed that observed changes in metabolic power, due to the variation of speed and body weight, did not result in parallel changes in the mechanical work done by muscles. These authors also suggest that the metabolic cost of generating muscular force during the foot-and-ground contact, regardless of whether the mechanical work (product of force by displacement) is produced (e.g., concentric contractions) or not (e.g., isometric concentrations), is what determines the rate at which energy is consumed. Shi and Stuhmiller[37] concluded that, for many activities, there is a relationship between metabolic cost and the magnitude and frequency of force application, linked to the effective contact time of the foot with the ground.

Very different changes in step frequency, in comparison with that considered natural, can induce significant changes in energy-minimizer mechanisms in walking. At a given speed, the recovery percentage tends to increase when the step length is greater than that observed in the natural gait and, conversely, tends to decrease when the step length is smaller than that freely chosen.[38]

The trunk coordination during the human march has also been a focus of study. In normal subjects, the increase in walking speed changes the phasic relationship between the rotations of the trunk and pelvis in the horizontal plane, so that at lower speeds these two segments tend to have a more synchronous behavior (in phase), that becomes more and more asynchronous (out of phase) as the speed increases. Thus, in a brisk march, the oscillatory movements of the trunk in relation to the pelvis become more evident. Although the mechanisms that govern such coordination are still not completely understood, even in normal subjects, in some disease conditions – such as in low back pain – there is a loss of this coordinative movement in a way that, even for higher walking speeds, both segments (trunk and pelvis) tend to move synchronously, forcing a more “en bloc” style of walking.[39,40]

Mechanical and energy losses during gait arising from low back pain

While normal subjects select their length and frequency of steps in order to make the most economical gait from the point of view of energy, those with diseases involving the locomotor system change that strategy. Large step lengths induce changes in the system of coordination between trunk and pelvis, implying larger rotations between these segments during walking. In pathological marches, there is a trend to avoid large oscillations of the column, and these individuals can do this in several ways; as to chronic low back pain patients, they tend to walk more slowly, decreasing the length and increasing, to a lesser extent, the frequency of their steps.[40]

Subjects with low back pain exhibit several adaptations during walking as a result of pain, such as: alteration of proprioceptive postural control; stiffer trunk and body strategy, leading to the adoption of the ankle strategy; increased activity of lumbar muscles during all step periods and, secondarily, less relative relaxation during swing periods, compared with double-stance periods; a decrease of the vertical component of ground reaction forces in those individuals whose pain is radiating to the lower limbs; a decrease in preferred walking speed; a decreased thorax-pelvic coordination in the transverse plane, inducing a more rigid behavior between these segments; a shorter step length, among others. Moreover, patients with nonspecific chronic low back pain, when asked to increase their walking speed, tend to increase more the cadence, rather than the length, of the steps, unlike individuals free of pain.[15,41-45]

Lamoth et al.[44] observed that individuals with low back pain who walked in the same relative speed (110% of preferred speed) of subjects without low back pain showed step length, walking speed and step length variability significantly lower, but this was not observed when the step frequency was evaluated. Elbaz et al.[46] observed that patients with nonspecific chronic low back pain showed asymmetry in their one-foot support and in swing and stance phases, in addition to a lower walking speed. These authors suggest that, in these patients, the decrease in walking speed can be understood as a protective mechanism attributed to an attempt to reduce the ground reaction forces and to minimize the overload in the column and avoid pain.

The pain, at least when it comes to walking, seems to play a more important role in acute episodes. Moe-Nilssen, Ljunggren and Torebjork[47] tried to find out if the measurement of the lumbar spine acceleration, quantified by an accelerometer, could indicate changes in motor behavior during walking, as a result of a transient low back pain experimentally induced by an injection of hypertonic saline into the longissimus dorsi muscle. These authors found a dynamic interaction between pain and adaptation in motor performance, when observing reduction of lumbar acceleration during the period of maintenance of induced pain, assuming that this change was processed by the vegetative nervous system.

Taylor, Evans and Goldie[48] compared a group of volunteer subjects with acute low back pain seven days after the onset of pain and six weeks later, when the pain had disappeared, and also evaluated subjects without low back pain. In each assessment all participants walked at the self-selected speed and at an intensity 40% faster than the self-selected speed. These authors observed that, at higher speeds, during the period of exacerbation the lumbar group exhibited significant adjustments in the way of walking, such as increases in pelvic tilt, in lateral flexion of the lumbar spine and in the step length *versus* post-test evaluation. However, no differences in relation to the control group were found. These findings suggest that the pain can cause changes in walking style.

In chronic pain conditions, an understanding of the adaptative processes becomes a much more complex task. Accordingly, other studies also shift the focus of pain as a determinant variable in the population of chronic low back pain patients, at the expense of the functional picture. The evidence suggesting that supraspinal changes (neurodegeneration of dorsolateral portion of prefrontal cortex; gradual decrease in neocortical, prefrontal cortex and thalamus gray matter volume, among others) present in patients with chronic nonspecific low back pain may contain the mechanisms that justify the clinical findings is increasing, although still without consensus about this supposition. Thus, it is believed that this reorganization within the brain is capable of generating a picture of persistent pain, even in the absence of physical change, and this includes the cortical neurodegeneration and descending inhibition, producing an abnormal state of sensitivity; memory of pain; and generation of central pain as a result of sensorimotor incongruence, when the patient is moving. Therefore, the motor changes observed in these individuals would have a central, rather than peripheral, origin, and this knowledge imposes the need to rethink both the nature of the problem as the best way to approach it, because, by all accounts, the physical changes cease to be the cause and become a result of a significant change in the central representation and in the attempts of the patient to maintain the same functionality, even in the presence of a changed body image.[49]

Other studies have also confirmed the changes in volume and density of the cortex as well as of the white matter among patients with chronic low back pain.[50-52] These changes were observed in several cortical areas, including those related with the speed of gait processing, as the corpus callosum, which also seems to be associated with poor physical fitness and duration of pain.[51] The structural and functional changes that occur in the brain of low back pain patients, suggested by these studies, give due credit to the hypothesis that these individuals are less able to adapt their spatio-temporal gait parameters, in comparison with pain-free individuals. Consequently, as the gait kinematics plays an important role in energy-minimizer mechanisms, the hypothesis proposing that these patients are also less economical becomes more robust.

Thus, it is important to identify whether the changes during gait, observed in this population, arise also from the inability of the body to provide an economical gait, or if they exist precisely to preserve the economy of gait.

At least with respect to the scope of this literature review, no studies correlating the motor losses in locomotion (widely described among chronic low back pain patients) with energy-minimizer mechanisms of walking were found. Therefore, this suggests the need for studies that seek to understand whether or not there is a loss of these mechanisms in this population.

Final considerations

The main theory explaining the minimization of energy expenditure during walking is the inverted pendulum mechanism, and the energy-minimizer mechanism of this theory would be the reconversion that occurs during the march, among the mechanical energies linked to the body center of mass (kinetic and potential energies). However, this energy-minimizer mechanism is strongly influenced by spatio-temporal parameters of gait which, in turn, may be severely altered in those individuals with chronic back pain. Thus, there is evidence that such functional changes may compromise the energy-minimizer mechanisms.

Conflict of interests

The authors declare no conflict of interests.

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