

## Article

# From Neural Command to Robotic Use: The Role of Symmetry/Asymmetry in Postural and Locomotor Activities

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**Abstract:** This article deepens a reflection on why and how symmetry/asymmetry affects the motor and postural behavior from the neural source, uterine development, child maturation, and how the notion of symmetry/asymmetry has been applied to walking robot design and control. The concepts of morphology and tensegrity are also presented to illustrate how the biological structures have been used in both sciences and arts. The development of the brain and the neuro-fascia-musculoskeletal system seems to be quite symmetric from the beginning of life through to complete maturity. The neural sources of movements (i.e., central pattern generators) are able to produce both symmetric or asymmetric responses to accommodate to environmental constraints and task requirements. Despite the fact that the human development is mainly symmetric, asymmetries already regulate neurological and physiological development. Laterality and sports training could affect natural musculoskeletal symmetry. The plasticity and flexibility of the nervous system allows the abilities to adapt and compensate for environmental constraints and musculoskeletal asymmetries in order to optimize the postural and movement control. For designing humanoid walking robots, symmetry approaches have been mainly used to reduce the complexity of the online calculation. Applications in neurological retraining and rehabilitation should also be considered.

**Keywords:** symmetry; asymmetry; human; development; locomotion; posture; walking robot



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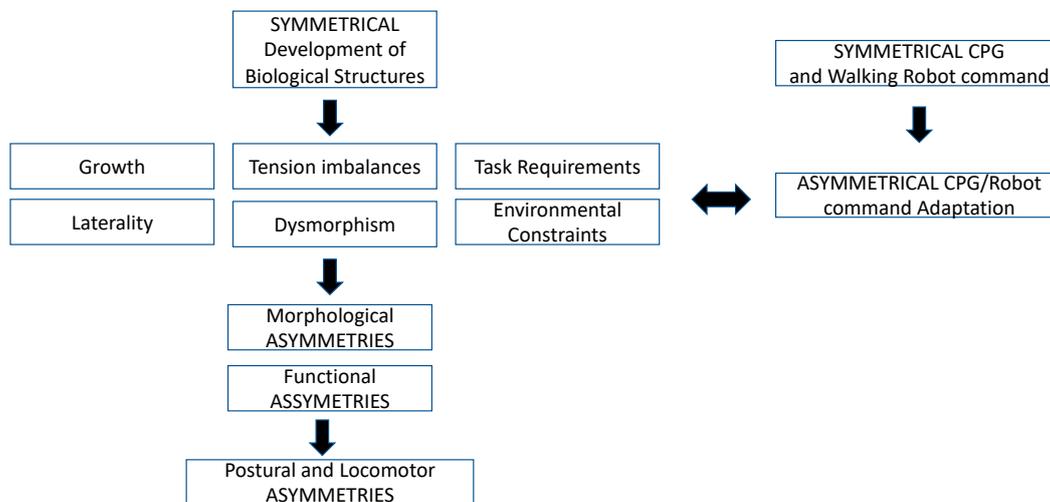


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## 1. Introduction

In order to achieve locomotor activity with a high level of symmetry [1–4], we can ask ourselves whether the components of our musculoskeletal system absolutely need to be symmetrical and whether the neural control that activates the functionality of our muscles should also be symmetrical. Figure 1 presents the conceptual elements taken into consideration in how we approach the notion of symmetry/asymmetry in the control of posture and locomotion. In this article, we will introduce the concepts of tension imbalance, tensegrity, and dysmorphism to illustrate how the biological structures have been influenced and altered during growth and maturation, the development of laterality, as well as the influence of task requirements and the environmental constraints. This article will also deepen the reflection on why and how symmetry/asymmetry affects locomotor and postural behaviors. Finally, we will present how the neural source for locomotion and the early humanoid walking robot commands were assuming symmetry

and how this command was adapted to more human-like environmental constraints and task-oriented requirements.



**Figure 1.** Conceptual elements taken into consideration in the symmetry/asymmetry approach in the control of posture and locomotion. CPG: central pattern generator.

## 2. Symmetry/Asymmetry in Human as Seen from Arts and Functional Anatomy

What is beautiful is symmetrical. From an aesthetic point of view, this is undoubtedly true. In general, symmetry is seen as attractive. In the classical Greek period, the Greeks possessed a sense of beauty. Indeed, Greek sculptures from the classical period such as the Lancelotti Discobolus (National Museum Rome) clearly demonstrate this sense of beauty. Greek statues and Renaissance sculptures, not to mention Leonardo da Vinci's Vitruvian Man, represent perfectly symmetrical human forms. It has long been the human morphological standard, and perhaps still is. During the Renaissance, Michelangelo's sculpture of David captured balance and harmony of forms and brought to the fore the notion of ideal form. Even to this day, bipedal postural analysis is based on this right/left symmetry of form as well as straightness and divergence of lines. Additionally, according to the principle of tensegrity (contraction of the words tension and integrity), a structure is stabilized by a continuous tension applied to discontinuous elements in compression. The architectural principle called "tensegrity" and put forward by Buckminster Fuller in the 1960s was inspired by a sculpture made by sculptor Kenneth Snelson in 1948 (the X-Piece). This principle is opposed to the traditional principle of man-made structures involving continuous gravitational compression. This implies that in weightlessness, these structures can lose their shape while the tensegrity structures retain it. Inter-limb symmetry/asymmetry may occur as a function of motor experience (e.g., high versus low), the nature of movements (e.g., specialized versus non-specialized), the environmental context (e.g., easy vs. difficult motor tasks), individual/intrinsic factors (e.g., afferences, hemispheric laterality, and motor output), and the limb dominance effect. However, on the one hand, the finer details of motor and postural symmetry/asymmetry have not yet been fully identified in terms of information perception, central integration, and movement command and control. On the other hand, the neural mechanisms involved are also not fully understood at the different neurological levels (peripheral, spinal, subcortical, and cortical). Therefore, exploratory research is needed in order to understand symmetry/asymmetry in terms of human movement and posture.

The perfect shape is desired by nature, and as long as the tensor elements, which are the skin, muscles, and fascia, have an optimal length, the symmetry of the shape will be respected. But what is it from a functional point of view? Why is right/left inter-limb symmetry so particular to human movement and posture?

First of all, where did the idea of symmetry come from? The notion of left/right symmetry has been a very well-defined concept, especially in the case of the human body, since the mid-1900s [5]. The common meaning given to bilateral symmetry is based on the notion of proportionality, balance, and concordance between the parts in order to form a whole. Looking at a given population, it is difficult to conceive that there is a single human morphology, a theoretical ideal shape that expresses left/right symmetry. However, in 1949, Françoise Mézières entertains the notion that there is a human morphology known as “normal” and symmetrical and all forms deviating from this human morphology constitute a set of characteristics allowing identifying dysmorphisms called biotypes [6]. In our classical language, there is no so-called “normal” morphology, but only various morphotypes such as ectomorph, endomorph, and mesomorph used to define persons according to their genetics. We can therefore consider that the human morphological phenotype is the expression of all genes. If human morphological symmetry exists, where does it come from? How is it defined?

“The molecules that make up cells and cells that make up tissues are continually renewing and the maintenance of the integrity of this behavior is living. This behavior is a manifestation of structure and structural stability and resulted in the establishment of spatial relationships that balance the individually destabilized structural elements” [7]. Undeniably, at the level of its neuro-fascia-musculoskeletal system, the human body corresponds to the definition of symmetry, namely, the right side is the identical reflection of the left side. We find exactly the same bone structures and the same myofascial structures on both sides of the body. In the frontal plane, the median axis of the body divides the body in two and highlights this symmetry whether the gaze is projected on the anterior or posterior part of the body. Symmetry brings a certain stability. Symmetrical structures therefore make it possible to distribute forces equally throughout the neuro-musculoskeletal system. The anatomical continuities between the different muscles allow reciprocal feedback to take place through multiple mechanical and nervous pathways, activation time, intensity, duration, and release of tissue deformation, the latter being precisely controlled by a variety of sensory inputs such as proprioceptors located in connective tissue.

The introduction of new concepts such as those related to the fascia system caused the musculoskeletal duality to become obsolete and replaced by the notion of the mesokinetic system binding bones, muscles, and connective tissues into a symmetrical and functional unit [8,9]. The mesokinetic system is a unifying structural whole. In this unifying whole, we find junctions (i.e., joints) of remarkable precision that intertwine with each other in order to provide a dynamic of free, flexible movement [10,11]. Because the entire system works as a whole, the functioning of the body can be revealed, regardless of the situation or position. Thus, the entire system from the cytoskeleton to the mesokinetic system plays a unifying role in the common goal of structural integrity and movement [12]. However, observation of human morphology reveals a more asymmetric aspect.

Human beings are complex organisms and at the same time have a relatively simple geometry constituting a complete functional unit. At the heart of this functional unity lies the very notion of symmetry. What the left/right morphological asymmetry represents in typical human adults is dysmorphisms and tension imbalances in the myofascial elements, not structural asymmetry. The tension imbalances in the myofascial elements could be explained, in part, by the directional asymmetry of internal organs. According to Klingenberg [13], the internal organs of the human body are organized according to a directional asymmetry, that is, the traits develop differently on the left and right side of the body, for example, the lungs, which have three lobes on the right side and two lobes on the left side. Moreover, the developmental rhythm of neuro-fascia-musculoskeletal system could also impose a certain form of asymmetry, but dysmorphism and tension imbalances should be considered the main sources of morphological and functional asymmetries. In this section, we have shown that structurally, the human body is developed with a symmetrical pattern. Morphological asymmetries are the results of myofascial imbalances and produce functional asymmetries in posture and locomotion.

### *Symmetry and Asymmetry in Humans: From Uterine Development to Adult Life*

From the beginning of intrauterine life, symmetry/asymmetry regulates development. The third trimester promotes the flexed position when the infant is crowded by the uterine environment and experiences rapid brain growth, mediating flexion (arms and legs bent and trunk tucked forward) [14]. Despite this temporal frame corresponding to non-goal-directed fetal motility [15], positioning in physiological flexion (flexion of the shoulders, hips, and knees, scapular protraction, and posterior pelvic tilt) is the ideal position of the newborn, as it promotes proper symmetrical joint alignment, supports neuromuscular development, and promotes self-soothing and behavioral organization [16,17]. Interestingly, the innate genetic instructions indicated an asymmetric anterior/posterior development where the antigravity muscles responsible for antagonist movements (extensor posterior postural adjustments) mature earlier compared to the flexors [15]. Indeed, many studies showed that tibialis anterior (TA) (ankle flexor muscles) plays a different role in the postural control of children compared to adults [18,19]. Berger's group [20] explained this ontogenetic difference by a more central regulation of flexor muscle activity compared to the extensor, which has an effective circuitry in the lower levels. Furthermore, the pathways that innervate TA muscles mature later than gastrocnemius (posterior muscle) pathways despite their similar distal localization with respect to the ankle [19] and create asymmetries in motor and postural behaviors.

During growth, a gradual symmetry in the body, organ, and tissue (lengths, areas, and volumes) can be observed. The development of the human brain is also a long-lasting process, which is mirrored by a multitude of developmental changes such as in motor behavior [15]. In fact, these neurological mechanisms evolve over time in a non-linear way in which we can observe a sudden rather than a gradual change with age [21]. The functional symmetrical topography of the brain is primarily driven by genetic instructions, the starting point for epigenetic cascades that allow abundant interactions with the environment and activity-dependent processes [22,23]. The interaction is bidirectional where experience affects gene expression and genes affect how the environment is experienced [23]. The environment and activity-dependent processes shape the brain, and a certain asymmetry could appear especially in the cortical homunculus mapping (for example, in the musician). The abundance of cerebral connectivity is the neural basis of human behavioral variability, i.e., the ability to select, from a large repertoire of behavioral solutions, the one most appropriate for a specific situation [15]. This flexible and adaptative neurological capacity allows the possibility to adapt their movement responses to the symmetric/asymmetric biomechanical demands from the task requirements and the environmental constraints. The period when major and rapid postural symmetric/asymmetric of growth changes occur corresponds to the time when the cerebral plasticity is increased (i.e., before adult age). Indeed, childhood and adolescence are sensitive developmental periods associated with an increasing sensorimotor experience leading to a different effect on motor behavior [24,25].

The non-monotonic pattern that dictates the rhythm of motor development of several parameters has been reported in studies assessing reactive postural adjustments [26], postural control adjustments during self-initiated unloading [27], goal-directed arm movements [28], stability limits [29], and quiet standing tasks [21,30–33]. Increasing evidence indicates that this period corresponds with a critical transition period for maturation (around 6 or 7 years of age).

One important hypothesis that has been proposed to explain these sudden changes in movement and postural control during the transition period is associated with nervous system adaptations in which the effectiveness of the processing and integration of multi-modal sensory information increase and evolve from an en bloc strategy (also named the ballistic strategy) from 0 to 5 years of age toward a sensory strategy that is mastered over 8 years [32,34]. However, it is possible that the transition period was a necessary sensory recalibration period after rapid development of the body segments in order to update the internal model (body image).

In fact, the growth of the different segments is not uniform and symmetrical. Surprisingly, a certain genetic asymmetry regulates the course of the lower limb. For example, the analysis of 354 unaffected hip–knee–ankle angles with anteroposterior full-length standing radiographs revealed that participants aged from 1 to 2 years old were naturally in varus ( $+3.6^\circ$ ) during the emergence of locomotor functions. However, the following year (2 to 3 years old) undergoes a drastic change in the hip–knee–ankle angles from  $6.1^\circ$  in the opposite direction in order to reach a valgus posture (means,  $-2.5^\circ$ ) [35]. This period corresponds to the development of dynamic postural control mechanisms, which allows controlling bipedal body posture during displacement and during active movements [36]. Postural control is intimately linked to motor control: dynamic motor actions cannot be performed without first stabilizing body posture [37]. In order to compensate for this asymmetric postural development and inexperience, children select the *en bloc* strategy that allowed the possibility to limit the degrees of freedom and facilitate the direction-specific postural muscles recruitment [15]. The *en bloc* strategy is dominant often between the ages of 9 months and 2.5 years old and is largely used until the transition period [19,34], corresponding with the drastic change in the lower limbs angle configuration. After the transition period, around the age of 8 years old, the lower limbs angle reaches the one of adults (i.e., varus posture of  $+11.2^\circ$ ) [35], and both populations use the sensory strategy [34].

During skeletal development, bones increase in size and mineral mass while their morphology adapts according to genetics and to mechanical constraints from the task demands and environmental factors [38].

Similarly, when researchers compared the bone mineral content and the bone density at a stressed bone site (the dominant arm in a tennis or squash player) with little or no bone solicited from the site of their non-dominant arm, the results show differences ranging from 10% to 15% after only a few years of practice [39].

It is no wonder that the development of laterality (neurological factors) can influence the development of morphological asymmetries.

Laterality is a complex concept. It is expressed in predominantly manual, ocular, pedal, and auditory preferences, differences in sensorimotor performance between preferred and non-preferred effectors, and directional tendencies. It is one of the expressions of functional hemispherical asymmetries [40] that defines functional superiority on one side. Genetically determined at birth, the majority of people [41] have a match between the hand used to write, the foot used to kick the ball, and the eye used to look through a telescope. A typical young child with a manual predominance will choose the writing hand in a spontaneous and natural way. It emerges around the age of 3 to 3.5 years [42] and continues to refine itself until the beginning of adolescence (laterality represented and projected in the absence of the object or of the person). Laterality is therefore part of the evolution of the bone growth and of gross and fine motor skills asymmetry.

In light of these postulates, the body representation (internal model) is possibly the most important link between symmetric/asymmetric morphological changes and their influence on movement and postural control. It assumes the existence of an internal representation of the “geometry of the body”, the ground reaction forces, and its orientation relative to the vertical [43]. The early perception–action coupling is a fundamental process that allows the correspondence between the perception of an action, its sensorimotor representation, and its realization [44]. This body representation develops during childhood through the regular and varied interactions of the senses, especially with proprioceptive information [44,45]. Overall, this highlights the importance of regular and varied experience for all populations, especially in children, in order to continuously update the body representation and reinforces the need to avoid early sports specialization.

Body segments, organs, and tissues develop in a symmetrical pattern from uterine to early childhood periods. Then, laterality and motor skills are developed under the influence of both environmental constraints and task requirements. Evolution of the early postural control patterns “*en bloc*” is progressively modified to a more adaptive and mature response.

### 3. A Central System for Locomotor Rhythm and Pattern Generation: Control of Symmetrical/Asymmetrical Activities by the Spinal Cord

More than a century ago, Graham Brown provided compelling evidence that locomotion was essentially controlled by a neuronal network located in the spinal cord [46,47]. In anesthetized cats, rabbits, or guinea pigs, he showed spontaneously occurring hindlimb stepping movements after a complete transection (Tx) of the spinal cord at the thoracic level. Given that (1) doses of anesthetic used by Graham Brown were known to abolish selectively proprioceptive and exteroceptive reflexes and (2) descending commands from the brain after a Tx could no longer exert control over hindlimb muscle contraction, he proposed the existence of a spinal command center located in lumbar segments, called the ‘half-center’, that would be responsible for locomotor rhythm and pattern generation in the lower limbs. He imagined the network to be composed of two groups of neurons, reciprocally connected and mutually inhibiting each other in such a way that activity in the first group (e.g., extensor half-center) would activate extensor muscles while inhibiting the reciprocal group of neurons (flexor half-center) for the concomitant relaxation of flexor muscles and execution of the stance phase. After a period of ‘depression’ of the extensor half-center due to fatigue (due to adaptation or post-inhibitory rebound), the second group of neurons (flexor half-center) would take over for the next phase of activity—e.g., the contraction of flexors, relaxation of extensors, and execution of the swing phase.

In the 1970s, the existence of such a central command center, thereafter called the Central Pattern Generator (CPG) for locomotion, was clearly demonstrated experimentally by Grillner and Zangger using completely deafferented spinal Tx animals [48,49]. In the meantime, another group of Swedish researchers obtained the first electrophysiological evidence of its existence in lumbar segments of the spinal cord (lamina VII) using intracellular recording techniques, L-DOPA injection, and flexion reflex afferent stimulation [50,51]. Still today, a plethora of studies are being conducted to identify further CPG elements and characteristics. Based on some of them, it is now generally accepted that the CPG is composed of genetically identified cells such as the HB9, V0, V1, V2, and Shox2 interneurons (for left–right coordination or rhythm and speed control), intrinsic cellular properties such as endogenous bursting neurons and Ih current (for pacemaker-like generation), specific pharmacological properties such as 5-HT1 and D1 receptors (for CPG activation), and complex network connections that support synaptic interactions as those proposed in the ring model, flexor burst model, or two-level organization model for distinct and selective rhythm and pattern adaptation [52].

In normal conditions, basic locomotor gaits such as straightforward walking at low speed are generally considered to be more or less symmetrically organized—that is, with a steady rhythm, pattern, and timing of muscle activity. For instance, at the ankle level, the medial gastrocnemius (extensor) will be typically contracted throughout stance and relaxed during swing with a rather strict out-of-phase relationship with its direct antagonist, the tibialis anterior. At other joints of the limb, comparable alternating out-of-phase relationships will also be found between agonists (extensors) and antagonists (flexors) unilaterally as well as between homonymous muscles bilaterally (left and right biceps femoris) during bipedal walking [53]. This said, multiple symmetrical patterns and gaits exist given that a wide variety of strategies can be used by animals, including humans, to move from A to B by swimming, flying, using bipedal or quadrupedal walking, running, or galloping. Yet, clear evidence shows that, among all vertebrate species, all gaits and forms of stereotyped rhythmic motor behaviors are similarly controlled by central centers such as the CPG in association with other sets of neurons located in the mesencephalic locomotor region (MLR) of the brainstem and elsewhere in the nervous system [54].

Otherwise, many conditions also exist for which asymmetrical muscle contraction can be found. Depending on species, gaits, goals, and/or imposed demands such as pathologies, amputation, overloading, or directional changes, different patterns of muscle activity have been reported. For instance, rather abnormal and more or less asymmetrical patterns were found in people diagnosed with the Uner Tan Syndrome expressing quadrupedal

walking [55]. In four-legged animals, patterns of muscle activity often differ considerably between slow (walking) versus fast locomotion (trotting, galloping), suggesting, in turn, the existence of a speed- or task-dependent reorganization of the CPG. For directional changes, asymmetrical or atypical muscle contraction is found, for example, to turn left during swimming; specific stimulation of some reticular formation nuclei, the Middle Rhombencephalic Reticular Nucleus, generally elicits, within a few milliseconds, a C-shape contraction of the entire body on the side of its new trajectory, momentarily replacing and resetting the regular left–right rhythmic pattern of axial muscle activity, which has led to the suggestion of a key role for this brainstem area in directional changes during locomotion [56]. Stimulation of other brainstem areas and nuclei was also found to trigger locomotor adaptations such as speed increase (Posterior Rhombencephalic Reticular Nucleus stimulation) or highly specific directional change and asymmetrical pattern (Anterior Rhombencephalic Reticular Nucleus stimulation for contralateral turns) [57]. Control over both initiation and speed adaptation has also been shown following stimulation of the MLR. Russians in the 1960s showed in decerebrated cats that weak stimulation of the MLR tonically, at the mesopontine junction of the dorsal reticular formation, could elicit walking in decerebrate cats, whereas stronger stimulation led to greater speeds and hence to gait alterations such as galloping instead of walking [58,59].

That great flexibility in pattern, speed, and gait enabled by CPG interactions with other structures including brainstem nuclei is not limited to the CNS. For instance, speeds can also be partially altered by peripheral-input-induced CPG mediated actions. One of the most relevant evidence has come from Forssberg and colleagues in the 1980s using Tx kittens walking on a two-belt treadmill—they showed that increasing speeds of only one belt did not prevent the other leg from walking ‘normally’ at lower speeds on the other belt [60]. Comparable observations made recently in adult cats suggest that adaptations of that nature, probably involving joint afferent inputs, remain possible in mature and chronically injured animals [61]. Other experiments with Tx cats performed by Forssberg [62] also showed that one leg perturbed after hurting an obstacle can express a bilaterally coordinated hyperflexion that brings the foot above and over the obstacle in order to maintain successful walking. Other receptor systems such as the proprioceptors have also been shown to play a pivotal role in CPG adaptation and asymmetrical control. When stimulated electrically during locomotion, muscle spindles (Ia afferents) and Golgi tendon organs (Ib afferents) were shown to enable extensive coordinated corrective responses expressed throughout the legs bilaterally—a form of temporary cycle-to-cycle asymmetrical adaptation in response to a sudden external disturbance (e.g., hole or overload). Only during locomotion (i.e., not at rest), group I afferents (Ia and Ib) from ankle extensors [63] or group II afferents from flexors [64], when stimulated briefly (100 ms), lead to CPG-mediated responses by replacing the correspondent classical reflex actions that promote the activity of extensors while inhibiting flexors throughout the entire limb in decerebrate cats.

All in all, the findings described above about locomotor-dependent responses (speed increase, gait alteration, directional change, extension enhancement, step cycle resetting, obstacle avoidance, hole, etc.) detected or stimulated suddenly by brief activation of specific peripheral receptor systems (cutaneous, joint, muscle Ia or Ib afferents) and/or central supraspinal structures (e.g., reticular formation, MLR, visual system, etc.) constitute examples that provide compelling evidence that the CPG is endogenously all set and prepared for a wide variety of symmetrical demands and of how these responses can be adapted with asymmetrical corrections under various environmental conditions and task requirement circumstances.

#### 4. Symmetry/Asymmetry from Robotic Point of View

Researchers studying human gait have approached its quantitative evaluation through various parameters: stride speed, stride length, step information (length, width, angle and time), joint angles, muscle strength, etc.). Regardless of the field of application (rehabilitation, sport, or robotics (humanoid or walking robot)) the factors (indices) that allow its

qualification are static or dynamic balance, stability, and symmetry/asymmetry, either to find a so-called healthy (or “normal”) gait, maximize performance, or simply reproduce human walking with a humanoid robot. They are characterized by the trajectory of the joints, left/right symmetry, center of gravity (CoG), center of pressure (CoP), ZMP, etc.; international research has provided many works that lead to two different approaches (or models).

The first is the oldest and most used. It consists of describing walking as a continuous sequence of cyclic articular rotations of the limbs and trunk [65,66]. This concept is generally applied, with left/right symmetry as a prerequisite, to robotic systems (to mimic and reproduce human walking movement). In this context, the stability index is always estimated by monitoring whether the expected performance remains stable. The imitation of walking is, however, limited by the complexity of the body structure and its controls.

The second is less widespread and can be defined as the “forward translation” of the body system through “total locomotion”. This movement results from the interaction between gravity, inertia, joint rotations, and the cyclic contraction of many muscles [67,68]. In this context, gait balance and symmetry are considered essential to maintaining gait translation performed by individual parts of the body. However, there is not yet a quantitative index to describe balance and symmetry, although many studies have been performed in this area.

Regardless of the approach chosen, the problem of asymmetry has often been studied and/or observed in people with neuromuscular pathology or alteration [65]. However, studies suggest that able-bodied people also sometimes exhibit asymmetric behaviors [2,69]. Understanding when and why this phenomenon occurs is important for gait research, where symmetry is typically assumed in order to simplify data collection and analysis. Many methods exist to quantify asymmetric movement between the right and left legs, using variables such as stride length [70–72], range of motion of the joints [73–75], velocity profiles [76] and ground reaction forces (GRF) [77–79], electromyographic profiles [80,81], limb forces and moments [82–84], or the oscillating center of mass [85,86]. However, the underlying causes are still the subject of debate. The functional asymmetry of gait hypothesis for able-bodied people suggests that each leg performs different roles, such as vertical support, medio-lateral (ML) control, and/or anteroposterior (AP) propulsion [2]. Differences between the roles of the legs have been observed in trials of brisk walking [87,88], suggesting that difficult locomotor tasks require asymmetric strategies. This is illustrated by asymmetry ratios in athletic walking [69] and running and cycling [89], which have been attributed to irregularities in the ground, footwear, and conditioning on the trails’ curves. The most common explanation for functional asymmetry is leg dominance, but conflicting reports exist for this theory [71].

In the context of robotics (walking robot and humanoid), symmetry essentially constitutes a strong hypothesis for reducing the number of parameters that characterize and define walking. This is explained by the fact that a humanoid walking model has a high degree of redundancy that can be solved or bypassed by fixing the values of certain parameters, by resorting to optimization, or by adding constraint equations. As a result, being inspired by human walking can constitute a means of lowering the degree of redundancy in a simple way, allowing the humanoid to acquire a more natural behavior, and he can have characteristics of lower consumption of energy on unstructured soil [62,90].

In this context, the management of the balance associated with symmetry is a recurring and unavoidable problem for the generation of bioinspired walking for humanoids. The latter can be static or dynamic. In static walking, the projection of the CoM in the horizontal plane must be permanently inside the support polygon (convex envelope including the points of contact between the feet and the ground). In the case of dynamic walking, dynamic stability is obtained by using various criteria, including, among the most used, ZMP (zero moment point) and CWS (contact wrench sum). The ZMP is the point of the ground where the resultant of the reaction of the ground produces a zero moment along the anteroposterior and transverse axes [91–94]. This widely used criterion in the

dynamic balance control of bipedal robots involves keeping the ZMP within the support polygon to prevent the foot from tipping over. Li and collaborators proposed a method that changes the position of the trunk when the ZMP deviates from the trajectory [95]. Other authors solve the problem of balance by modifying the position of the upper body [96–98] or the orientation of the trunk [99] or the waist position [100]. We can also note the use of the center of mass (CoM) to dynamically control a biped. The principle consists of controlling/regulating the acceleration of the CoM and ensuring a good distribution of the interaction forces between the segments and the trunk [101–104]. The CP (crossing point) refers to a virtual point located between the hip line and the ankle with each line to the left and right, respectively. The CWS was proposed [105] in the context of legged robots; it is based on the sum of the forces applied to the robot's CoM: if the sum of the forces of gravity and inertia applied to the CoM is inside the polyhedral convex cone of the contact forces between the robot's foot and the environment, then the balance is guaranteed. He extended and used this criterion on a humanoid on flat ground, to climb stairs, or on uneven ground [105]. We can also note the crossing point (CP) proposed by Kim and collaborators [106] and the foot rotation indicator (FRI) proposed by Goswami and their colleagues as another index used [107].

Another aspect to consider is that body mechanics are responsible for functional asymmetry. Simulation work has shown that the momentum and gravity are sufficient to propel the walking movement on a low slope [108,109]. These passive models reflect certain characteristics of human walking, such as ballistic movement during the oscillation phase [110] and energy efficiency on low slopes [111], and therefore act as simple substitution models for the study of bipedal mechanics. Although the dynamic equations of motion can give a stable solution corresponding to a symmetrical gait, small changes in the model parameters can result in qualitatively different behaviors at a bifurcation point, after which a new asymmetric (stable) solution emerges from the symmetric solution (unstable). The symmetrical mechanics of these walkers admit two families of solutions, one symmetrical and the other asymmetrical. However, the functions of these asymmetries have not been studied, and the period doubling phenomenon has not been shown to extend to more realistic 3D models that walk on flat ground.

On balance, symmetry/asymmetry serves to simplify and reduce the complexity of biological reality or a model, making it a powerful tool in robotic applications or related to computers and analytical modeling. Philosophically, does biological symmetry really exist? From this point of view, then one can question of the relevance of the models with a perfect symmetry—are they false for all that?

## 5. Conclusions

In conclusion, the development of the brain and the neuro-fascia-musculoskeletal system seem to be quite symmetric from the beginning of life through to complete maturity. The neural sources of movements, i.e., CPGs, are able to produce both symmetric or asymmetric responses to accommodate to environmental demands and task constraints.

Although the human development is mainly symmetric, asymmetries already regulate neurological and physiological development. The laterality and regular sports training could affect the natural musculoskeletal symmetry. The plasticity and flexibility of the nervous system allow the abilities to adapt and compensate for environmental constraints and musculoskeletal asymmetries in order to optimize the postural and locomotor control. For designing humanoid walking robots, symmetry approaches have been mainly used to reduce the complexity of the online calculation. With the improvement of computer power capacity progress, asymmetrical body models might be added in future walking robot developments. Applications in neurological retraining and rehabilitation should also be considered.

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