Sitting-walking Derived from Tai Chi Gait: A Fundamental Improvement to Fall Prevention in Older Adults (Part 1)—Characteristics of Sitting-walking

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Abstract

Tai Chi (TC), a traditional exercise originating in China, is increasingly being recognized for its health benefits, especially in older adults, including fall prevention. TC has always been regarded as an alternative or auxiliary exercise intervention to prevent falls in older adults. The training and evaluation adopted focused on strengthening the muscle strength and balance ability of the lower limbs, and the exercise forms adopted were mainly actions and movements, a few of which focused on the TC gait (TCG). These factors cause the fall prevention effect to become unsatisfactory. There are different views on this topic in academic circles. This is related to a lack of understanding of the movement principles and mechanisms of TC. The authors believe that the solution to the problem of fall prevention should focus on the gait itself and that the uniqueness of TC is largely reflected in the gait. Through years of exploration and research, the authors applied TCG to daily walking and created a unique sitting-walking (SW) mode to fully exploit the function of TC in preventing falls. Its advantages in balance and its role in fall prevention in older adults are found in practice and teaching, which are discussed in Parts II and III of this series of papers, respectively. Based on a comparison with normal walking (NW), this study qualitatively describes SW from gait events, movement process, energy form, and walking posture, and lays the foundation for the discussion of the latter two parts.

Keywords

Tai Chi gait, normal walking, sitting-walking, fall prevention, older adults

1. Introduction

Tai Chi (TC) is a traditional Chinese exercise with many health benefits, such as maintaining balance and bone health, improving muscle function, promoting mental health, and improving overall health and quality of life [1-4]. In particular, TC exercises may have a potential effect on reducing falls [5]. This indicates that TC training improves the ability to tolerate instability [6]. These findings demonstrate that TC can reduce the risk and fear of falling among older adults [5, 7]. This shows that TC can play a positive role in health, particularly in older adults who prevent falls both physically and psychologically.

TC is therefore considered a promising exercise intervention method [5, 8-11]. It has recently been recognized as
an effective intervention, especially for the prevention of fall risk in the elderly [9, 10].

However, there are different views regarding the role of TC in fall prevention. To date, many randomized controlled trials (RCTs) have been conducted to evaluate the effect of TC in preventing falls [2, 5, 12], whereas clinical trials [1, 5, 13-15] and systematic evaluations (SRs) [16-18] have been conducted to study the effectiveness of TC in improving and reducing falls [19]. However, the results of these studies have been inconsistent [2, 5, 12, 19]. Loghe et al. suggested that there is insufficient evidence that TC can reduce the incidence of falls [20].

To a large extent, the different conclusions on TC fall prevention are related to the understanding of the movement principle and physiological mechanism of TC, as well as the perspective and method adopted by the research.

Although reports in Chinese literature show that TC practice has great psychological and physiological benefits, there are no confirmatory data or comparative studies in Western scientific literature to support such claims [21]. A growing body of evidence suggests that TC improves balance and postural control, thereby reducing the number and risk of falls; however, the underlying mechanisms remain largely unknown [5]. This indicates that the physiological mechanism of TC remains unclear in academic research. Therefore, without a thorough understanding of these mechanisms, it is difficult to accurately identify and effectively apply optimal forms of TC to interventions to prevent falls in the elderly [22].

To date, TC training is mainly through the practice of TC sets composed of movements or forms as the basic approach and is focused on strengthening lower limb muscle strength and balance through TC; the research is based on these training results. The evaluation criteria for other sports are adapted to evaluate the effects of TC.

TC is only discussed in terms of movements or forms (sets), namely TC sequences, which not only touch on the superficial form of TC but also bring great limitations to its practice. On the one hand, the complexity and duration of the traditional TC (tTC) sequence may be too challenging for some elderly people [23, 24]. And intense TC training in older adults “transitioning to frailty” (based on attributes described by Speechley and Tinetti [25]) is not effective in reducing the risk of falls [26, 27]. Therefore, not all older people can complete TC programs [23, 24]. On the other hand, even though individualized TC (iTC), as mentioned by Penn et al. [28], provides better results than tTC, it only reflects the influence of lower limb function, balance control, and muscle strength. It has been suggested that TC is a suitable form of balance and leg strength training [27].

TC improves the strength and balance of lower-limb muscles because of its emphasis on lower-limb stability. However, TC is not simply an exercise aimed at improving the muscle strength of the lower limbs to achieve balance because it focuses on bone training rather than muscle training. TC exercises emphasize spatial changes in the body while muscles are relaxed, which is the result of internal movement. Simultaneously, TC focuses on the rationality and stability of the overall posture of the body, especially stability in the state of activity or external interference, thus forming the dynamic balance ability of the body with full flexibility and adaptability. Therefore, it seems biased to examine the anti-fall effect of TC only in terms of lower-limb muscle strength and static balance ability.

Some selected TC forms have been used in previous TC-based clinical trials [22]; however, this choice is devoid of scientific reasoning [14, 15]. It is also a major mistake to learn various movements (sets) at the beginning, ignoring basic training, including the most important TC gait (TCG). In fact, the movement principles and mechanisms of TC are fundamentally different from those of other sports. It can be said that if TC is regarded as a sport that is only different from other sports in form, it indicates that the movement principles and mechanisms of TC are not very clear. Therefore, if the effects of TC training are assessed only with tests typically applied to health-related fitness or competitive sports [29], the results may not be the most objective.

The real utility of TC is not achieved simply by strengthening the muscle strength and balance control of the lower extremities, nor is it solely derived from complicated and difficult movements. However, it is difficult to benefit from TC without understanding its movement principles, physiological mechanisms, and basic training skills. Unfortunately, with the increasing popularity and spread of TC, traditional, time-tested forms and training principles have been lost in increasingly personalized interpretations [6]. Forms without principles are considered "empty" or "devoid" of real substance, while fragmented or distorted TC forms lacking basic principles hinder progress and produce even fewer benefits [6]. Therefore, TC fall prevention should be based on a thorough understanding of this mechanism [22].

According to traditional TC practices, great attention is paid to the learning and training of basic skills, for which TCG training is an important link. The movement principle and mechanism of the TC were fully reflected in the TCG. TCG represents the essence of TC [30]. While TC involves the movement of many body segments, leg movement provides the foundation for balance and stability [30]. Therefore, movement training can only be performed when basic TCG is mastered. In other words, movement is simply the application of the body and hands to different states through gait changes. The proverb of TC says, “The hand goes 30 percent, while the leg goes 70 percent.”
The author’s master suggested that “there are no hands in TC; only feet walk freely.” This has a deep meaning that has not been expanded upon here. However, these all emphasize the importance of gait, which also shows that TC pays more attention to gait than to hands. The key to dynamic balance also depends on the gait. It can be said that it is difficult to truly benefit from TC without mastering TCG. The view that lower-limb muscle strength plays a major role in balance is also based on the reason for normal walking (NW) gait and posture, which makes the maintenance of NW balance largely dependent on the role of muscles. This is one reason why older adults are prone to falls when their muscle strength decreases. Gait is the focus of this study and will be discussed in detail later.

In conclusion, previous studies on TC in fall prevention mainly focused on improving lower-limb muscle strength and balance ability through TC set training; however, the individual's walking pattern was still based on NW gait. The proposed fall prevention methods are also based on the premise of strengthening, maintaining, or adapting to the NW gait. Thus, TC plays an auxiliary role in this process, only as an intervention or exercise based on NW. Therefore, TC is considered an alternative or auxiliary program to provide Western-style exercise programs [8].

Although muscle strength and balance ability of the lower limbs play important roles in preventing falls, the authors believe that gait is a crucial factor. Some TC masters in China remain nimble and steady in old age, both in practicing TC and in daily walking, not simply by strengthening the muscle strength of the lower limbs or by enhancing static balance ability. The key lies in the unknowingly changed gait habits after several years of TCG practice. Training TCG is the most direct method for preventing falls and is more fundamental than training for fall prevention through a variety of complex TC movements.

In the process of practicing TC for decades, the author has fully realized the magical effect of TCG on balance. However, it is not realistic to perform daily walking using pure TCG. Because ordinary people, especially the elderly, tend to fall while walking, the author has applied the principle of TCG to daily walking after years of exploration and experimentation and created the so-called sitting-walking (SW) [31]. Over the years of practice and teaching, the positive effects of this SW mode derived from TCG in improving dynamic balance, thereby reducing the risk of falls (fall prevention), have been consistently tested. To the best of our knowledge, only a few studies have been conducted on this topic.

However, the SW mentioned here is simple but not easy. “Simple” refers to its use in actual application processes, whereas “not easy” refers to the need to overcome habitual gait patterns during training. It should be said that SW is neither a form of auxiliary movement nor a form achieved by repeating and strengthening the original habits. It is essentially a new walking mode or a new walking skill. The key is fundamentally changing the previous NW mode and habits through practice. Therefore, this is a highly subversive and revolutionary challenge for human walking.

This series of papers will be divided into three parts to qualitatively describe the characteristics of SW (Part I), the advantages of SW (Part II), and the fall prevention effect of SW on older adults (Part III) based on a comparison with NW. It is hoped that this paper will help people roughly understand the SW mode and further promote the role of TC in preventing falls. This also lays the foundation for future quantitative studies.

2. Characteristics of sitting-walking

Sitting-walking, that is, walking in a sitting state. While walking, the center of mass (COM) of the body is always placed on the supporting leg, similar to a chair. Because sitting itself has the characteristics of balance and stability, SW also has these characteristics [31]. The gait mode of SW is significantly different from that of NW. To describe the characteristics of the SW mode more clearly, based on a comparison with the NW mode, a qualitative description is made of the aspects of gait events, movement process, energy form, and dynamic posture.

2.1 Sitting-walking gait events

With regard to NW, according to Sutherland and Cooper cited by Kaufman and Sutherland [32], the items of gait events were 1) foot strike and 2) foot-off. As there are two extremities, there are four items: foot strike (FS), opposite foot-off (OFO), opposite foot strike (OFS), and foot-off (FO) [32].

In the SW, the foot touches and leaves the ground differently than in the NW. The foot neither touches the ground in the form of a strike nor lifts off the ground in the form of pushing off. However, there is a key process of COM transformation during a two-foot landing. Therefore, the SW gait events included foot landing/tapping, COM transformation, and foot-off. With two extremities, there are six items in a complete gait cycle: foot landing (FL), opposite COM transformation (OCOMT), opposite foot-off (OFO), opposite foot landing (OFL), COM transformation (COMT), and foot-off (FO). Walking is accomplished by alternating movements of the lower limbs [33].
NW, the lower limbs go through two stages: the swing phase, or recovery phase, and the stance phase, or support phase [33]. During the SW process, the lower limbs undergo two stages. However, because the motion principle of the swinging leg and the function of supporting the leg is different, the two stages of SW are named the landing phase and the dangle phase [31] to distinguish and define them more accurately.

The landing phase includes single-foot landing (SFL) and double-foot landing (DFL). The SFL period is known as the single-leg standing/bearing stage and is divided into early, mid, and late stages. The DFL period is also divided into early, mid, and late stages, corresponding to the hindleg-bearing, COMT, and foreleg-bearing periods, respectively. The COMT period is divided into the initial, middle, and final stages.

The dangle phase is the period during which the opposite foot lifts off the ground and swings forward from the back, with the leg in a state of unilateral leg support. It can be divided into early-, middle-, and late-dangle stages, which correspond to the early, middle, and late SFL stages, respectively.

The SW process can also be divided into three stages: gait initiation (GI), stepping, and gait termination (GT). However, because the gait modes of SW are essentially different from those of NW, even if they are similar in appearance, the principles of movement and body posture are different. Therefore, their movements cannot be borrowed from each other. Therefore, to avoid confusion, traditional concepts related to the gait cycle of the NW are no longer used in the description of the SW gait modes.

2.2 Sitting-walking movement process

As a motion, the entire SW process also involves issues of movement mode and body displacement.

2.2.1 SW movement mode

During NW, one foot or the other is always on the ground, but both feet stand on the ground for a period when the support of the body is transferred from the hindleg to the foreleg [34]. Cyclic changes in the support function of each leg and the existence of a transition period when both feet stand on the ground are basic features of the movement process known as walking [34].

In terms of form, the SW also exhibits this type of movement process and its characteristics. However, the transitions between the support legs and between the SFL and DFL are not the same in the SW and NW. It should be noted that SW meets the two basic conditions of walking mentioned by Inman et al. [34]: (1) continuous ground reaction forces (GRF) supporting the body and (2) periodic movement of each foot from one support point to the next in the forward direction. However, the GRF generated during SW is also different from that generated during NW. In addition, there is a unique form of COM transformation during SW in the transformation of the foot support points. This is discussed later in this study. The following is a brief introduction to the movement process of several items involved in gait events based on flat walking. For the sake of description, the right leg is used as the unilateral leg and the left leg as the contralateral leg. The terms “left and right legs” or “front and back legs” are occasionally used in the description.

(1) The movement of the landing phase

It includes the movements of SFL and DFL.

The movement of SFL occurs when the foot lands on the ground while the other foot is off the ground. The contralateral support leg remains relatively static during the dangle of the single leg, with the head and torso upright and synchronized with the support leg and the pelvis tilted unilaterally. The COM of the body is always placed at the base of support (BOS) of the supporting leg throughout the process. Early SFL occurs when a unilateral toe lifts off the ground until the foot is adjacent to the contralateral support leg; mid-SFL occurs when the unilateral swing foot is adjacent to the contralateral support leg; and late SFL occurs when the unilateral foot swings forward from the adjacent side of the contralateral support leg until the heel touches the ground.

The movement of DFL occurs when both feet land simultaneously. This process starts with the heel of the unilateral foot touching the ground and continues until the toe of the contralateral foot is off the ground. During hindleg bearing (i.e., early DFL), the head and trunk are upright and synchronized with the hindleg, and the COM of the body rests on the hindleg and is placed on the BOS while the forefoot lands naturally. During foreleg bearing (i.e., late DFL), the head and trunk are upright and synchronized with the foreleg, and the COM of the body rests on the foreleg and is placed on the BOS, while the hindfoot lands naturally. What happens during COMT (i.e., mid-DFL) is the movement of the COM from the hindleg to the foreleg. The pelvic movement plays a major role during this period. In the initial COMT, the COM moves from the hind leg to the middle of the leg. In the middle COMT, the COM passes through the middle of the legs. In the final COMT, the COM is moved from the middle of the leg to the foreleg. During hindleg bearing (i.e., early DFL), the pelvis is inclined to the side of the foreleg. At the beginning
of COMT, with the relaxation of the hips, the pelvis begins to lower on the hindleg side (contralateral) and enters the initial COMT. At this time, the contralateral heel pushes against the ground to generate power, and the trunk synchronizes with the pelvis and moves with the pelvis (continuing contralateral lowering) in the direction of the foreleg (unilateral). When the middle position of both legs (i.e., the middle COMT) is reached, the pelvis is horizontal. Subsequently, the pelvis continues to descend to the opposite side until it tilts toward the hindleg and rotates forward, and the body continues to move to the foreleg, entering the final COMT. When the COM is moved to the BOS of the foreleg and enters the foreleg bearing (i.e., the late DFL), the trunk and pelvis face straight ahead. The toes of the hindfoot are not off the ground until COMT is complete. During the entire SW process, the COM of the body moves only during this stage, and it moves within the BOS formed by the feet. The head and trunk are upright and move horizontally with the COM in the direction of the foreleg.

(2) The movement of the dangle phase

It occurs when the unilateral leg swings from the rear to the front, that is, from the unilateral toe off the ground to the heel on the ground. The dangle begins at the end of the late DFL (i.e., foreleg-bearing period). When the COM is shifted to the foreleg, the pelvis tilts laterally on the foreleg as the support leg, whereas the unilateral leg bends at the knee and toes off the ground and begins to swing forward. Movement in the early dangle phase occurs when the unilateral toe leaves the ground and is adjacent to the opposite support leg, corresponding to the contralateral early SFL. Movement in the mid-dangle phase occurs when the unilateral foot is adjacent to the opposite support leg, corresponding to the contralateral mid-SFL. Movement in the late dangle phase occurs when the unilateral foot swings forward from the opposite support leg to the foot touching the ground, which corresponds to the contralateral late SFL. Throughout the dangle phase, the COM of the body is always located at the BOS of the opposite supporting leg.

2.2.2 SW body displacement

During NW, when the body passes through the weight-bearing limb, there will be three different deviations on the straight line; that is, with each step, the body will accelerate and decelerate slightly, rise and fall (a few centimeters), and shake slightly from side to side [34]. During walking, the body acts like an inverted pendulum, with the walker's COM rising and decelerating during the first half of the stance phase and then descending and accelerating during the second half of the stance phase [35-38]. Therefore, the body leans backward and forward during the early and late stance phases, respectively. The body also tends to move laterally over the support limb during single support because the amount of lateral sway increases with tread width [34].

During SW, the body displacement in space is different from that in NW. During movement, the body is always accompanied by a change in acceleration and deceleration, which are mainly completed in the COMT. However, regardless of the SFL or DFL, the body hardly rises or falls, leans forward and backward, and shakes from side to side. In the sagittal plane, it moves forward horizontally, and in the frontal plane, it moves horizontally to the left and right. However, the lateral shift of the body is smaller than that of the NW.

The DFL of the SW is different from the dual weight-bearing of the NW. During double weight-bearing in NW, the pelvis is horizontal, the COM is at its lowest point [34], and neither leg moves. COM displacement is achieved through the rise of the COM when the hindfoot pushes off the ground and the fall of the COM when the forefoot touches the ground. During the COM of the SW, the COM is shifted through the pelvis's lateral inclination and forward rotation, supplemented by the flexion and extension of the legs. The COM shifts forward and sideways in the horizontal plane during this process.

The internal mechanisms of the SFL and dangle phases of the SW are different from those of the single stance and swing phases of the NW. The single stance during NW represents an inverted pendulum. The COM of the body is always outside the BOS, moving from back to front in the sagittal plane and deviating from the side of the support leg in the frontal plane, accompanied by ups and downs. In the SFL of the SW, the support leg remains relatively static, and the COM of the body is maintained in the BOS (located near the lateral part of the heel) and does not change with the spatial position of the dangling leg. At the end of the dangle phase, the forward heel touches the ground lightly, and the COM remains on the hindleg at the moment of landing. The COM displacement trajectories of the NW in both the sagittal and frontal planes are sinusoidal [38]. The COM displacement trajectory of SW presents a nearly horizontal straight line in the sagittal and frontal planes.

In short, the body in the SW is not like an inverted pendulum but a forward translation (accompanied by side-to-side) like a vertical pole. The COM also accelerates and decelerates with the movement of the body but hardly rises or falls.
2.3 Sitting-walking energy form

Animals must produce and dissipate mechanical energy (i.e., positive and negative work) to accomplish movement [39]. The only source of mechanical energy production in the human body is muscle, which is also the main tissue for energy absorption [40]. During movement, mechanical energy continuously flows from one body part to another [41].

In NW, both positive and negative work in level or non-level gait is directly produced or dissipated by skeletal muscles through shortening (concentric) or lengthening (eccentric) contractions [39]. Negative energy keeps the walker upright, while positive energy pushes the walker forward [42]. This study reflects the change in gravitational potential energy (GPE) of the mass of an object when proceeding at a constant average velocity [43-47]. The other potential energy is elastic potential energy (EPE), which cannot be directly evaluated during gait [48]. However, the EPE of the lower limb muscles and tendons changes during walking and other activities [48]. The energy of human walking is exchanged between kinetic energy (KE) and potential energy (PE) [34]. In the NW, during the first half of the stance phase, the KE is converted to the GPE [49]. During the second half of the stance phase, the opposite transition occurred [50]. At the end of the stance phase, the peak positive energy occurs when pushing off to propel the limb into the swing [51]. In addition to maintaining balance during transitions, gait termination (GT) must dissipate energy, and gait initiation (GI) must inject energy into body parts [52].

In SW, the KE originates from the hindfoot pushing on the ground during the DFL. The PE in the SW is mainly represented by EPE rather than GPE. Therefore, the change in energy manifests as a conversion of KE to EPE. In the DFL, the moment of the transition from unilateral hindleg bearing/standing to the initial COMT is accompanied by relaxation of the hip of the unilateral support leg (the pelvis tends to fall on this side), while the unilateral heel pushes against the ground to generate KE. The pelvis, with unilateral inclination and forward rotation, moves in the direction of the foreleg, while the trunk simultaneously moves in the same direction. When the COM of the body shifts to the foreleg, that is, the transition between the final COMT and foreleg weight-bearing/standing, the pelvis tilts to the hindleg, and the KE reaches its peak. The hip is relaxed, the pelvic lateral tilt increases, the knee of the hindleg is bent, the heel is lifted until the toe is off the ground, and the early dangle phase (corresponding to the early SFL) is entered. Subsequently, the hip flexors are slightly contracted, and the unilateral hindleg begins to dangle forward. When the dangling leg passes through the opposite support leg, the hip extensor muscles are relaxed to maintain the hip in a relaxed state (corresponding to the mid-dangle and mid-SFL), and the unilateral leg continues to swing forward and downward owing to the inertia. During this process, relaxation of the soft tissues of the pelvis and hip increases the lateral tilt of the pelvis, resulting in the physiological prolongation of the unilateral leg (generating EPE). The KE is converted into the EPE, and the EPE reaches its maximum when the unilateral foot touches the ground at that moment (corresponding to the late dangle and late SFL). Subsequently, an early DFL is performed. At this point, the contralateral leg becomes a weight-bearing leg. At the initial COMT, the energy consists of the EPE released by the soft tissues and the KE generated by the heel pushing against the ground. The faster the walking speed or the longer the stride, the more energy is required and the greater the force of pushing against the ground. It should be said that the conversion from KE to EPE is completed in the early DFL. The maximum KE is reached during the late DFL. KE is generated in the mid-DFL (COMT). The conversion from KE to EPE is completed in the dangle or SFL phases.

The KE of the NW reaches its maximum when the heel strikes the ground, which leads to a large amount of negative work being required to control the body leaning forward, and the body is prone to imbalance. In contrast, the EPE of the SW is the largest when the forefoot touches the ground, which reduces forward inertia, and the COM is placed on the hindleg to balance the body.

2.4 Sitting-walking’s dynamic posture

Regardless of the type of movement that occurs in the limbs, a certain posture is assumed. Walking is mainly based on lower-limb activities. Therefore, walking first involves lower-limb posture. Walking is a holistic motion, which means that the head, arm, and trunk (HAT) postures are represented during walking.

2.4.1 Head, trunk, and pelvis posture

(1) Head posture

During NW, there is no difference in the magnitude of lateral displacement of the pelvis and head [53]. There is also no difference in the vertical displacement of the pelvis and head; however, movement in the forward direction is not coupled between the two [54]. In a mature gait, the separation of the head and trunk is greater [55]. To maintain eye and ear level, the head moves accordingly: it translates up and tilts down during the initial swing and translates.
down and tilts up during the terminal stance [55]. In SW, the posture of the head and neck is relatively upright; that is, the lower neck is basically vertical, the upper neck is slightly flexed, the jaw is naturally retracted, the head is upright, and the eyes look straight ahead [31].

(2) Trunk posture

During NW, the trunk moves in three anatomical planes: sagittal, frontal, and transverse. In the sagittal plane, the trunk changes twice during the gait cycle: maximal trunk flexion is found at heel strike, whereas maximal trunk extension is found during a single stance [56]. That is, the trunk leans forward and downward in the terminal stance and backward in the initial stance to the midstance. In the frontal plane, trunk motion tends toward the unilateral standing limb, reaching its maximum when the contralateral toes are off [57]. The trunk is inclined toward the side on which the foot touches the ground. The trunk was rotated in a transverse plane. The ipsilateral shoulder is located posterior to the heel striking limb, almost directly above the foot during midstance, and anterior to the stance limb near toe-off [57]. In fact, when walking at a high speed, the rotation of the trunk is opposite that of the pelvis [58].

During SW, the trunk was upright. The waist is straight (flat), which eliminates obvious lordosis of the lumbar spine (described in the author's book Tai Chi Medication). Trunk movement is synchronized with the pelvis. Except for a slight rotation of the pelvis during COMT, the trunk is oriented forward at other stages.

(3) Pelvis posture

In the human gait, the pelvis moves around one of the three cardinal axes [59]. The pelvis rotates forward and backward in the transverse plane around the vertical axis [60], also known as anterior and posterior rotation [61], or internal and external rotation [62]. The pelvis rotates in the frontal or coronal plane from side to side around the anterior-posterior axis (i.e., lateral tilt) and rotates back and forth around the mediolateral axis (i.e., anterior-posterior tilt) [61].

Pelvis rotation During NW, the pelvis rotates alternately to the right and left about the vertical axis relative to the line of advance [34]. When one foot first touches the ground, the pelvis rotates backward, which continues briefly during the double stance phase and then changes to the pelvis rotating forward, which continues until the contralateral heel strikes [61]. An increase in speed will result in an increase in pelvic rotation [63, 64]. In SW, pelvic rotation mainly occurs during COMT. During unilateral hindleg bearing, the pelvis faces straight ahead. In the initial COMT, the pelvis first rotates externally and continues to rotate externally in the mid-COMT until it rotates internally in the final COMT. When entering the foreleg-bearing position, the pelvis returns to the front. The pelvis remains in the forward direction throughout the SFL. The pelvis does not rotate during the GI or GT phases. The trunk is always synchronized with pelvic rotation.

Pelvis lateral tilt In NW, the pelvis lists downward in the coronal plane on the side of the non-weight-bearing limb (positive Trendelenburg) [34]. The peak of pelvic inclination occurs immediately after the opposite foot is off, corresponding to the early single stance [32]. At midstance, the pelvis is almost level [65]. In SW, the pelvis is in alternating lateral tilt changes, except for the instantaneous level in mid-COMT. In GI, the pelvis first inclines toward the non-weight-bearing unilateral leg, and then the unilateral leg swings out and lands on the ground, entering the weight-bearing/standing period of the contralateral hindleg (i.e., early DFL). The pelvis then externally rotates and descends on the weight-bearing side (i.e., the initial COMT) and moves toward the unilateral leg. During this process, the pelvis continues to descend contralaterally and ascend unilaterally until a brief horizontality occurs during mid-COMT. Subsequently, the pelvis continued to move toward the unilateral leg while continuing to descend toward the contralateral side. At the final COMT, the pelvis stopped moving and tilted toward the contralateral side. Finally, the pelvis rotates internally, faces straight ahead, and enters unilateral foreleg bearing (late DFL), at which point the pelvic tilt reaches its peak. The pelvis maintains a maximum contralateral tilt throughout the dangle phase. However, this differs from the Trendelenburg gait [32]. This maximal pelvic tilt in SW is the result of the individual actively relaxing the weight-bearing hip abductor muscle, whereas the pelvic tilt observed in Trendelenburg gait is caused by unilateral hip abductor weakness.

Pelvis anterior tilt In NW, after the initial contact, the pelvis tilts backward and then forward again until the opposite foot touches the ground; thus, the cycle is repeated [61]. The minimum anterior tilt of the pelvis occurs at foot-off, whereas the maximum anterior tilt occurs in mid- to late-stance and terminal swing [32]. However, in the sagittal plane, the pelvis generally remains antverted throughout gait [66]. During SW, the pelvis does not tilt back or forth and maintains a nearly vertical posture. It is accompanied by a falling of the tailbone, straightening of the lumbar spine, and slight hip flexion.

2.4.2 Lower-limb posture

(1) Hip posture

The hip joint can rotate about three axes: flexion/extension, abduction/adduction, and medial/external rotation
[32], which occur in the sagittal, frontal, and transverse planes, respectively.

During NW, 1) flexion and extension: the hip of the unilateral leg is flexed from the terminal swing to the initial contact until the opposite foot touches the ground [32]; 2) adduction and abduction: the hip is near maximum abduction from the toe-off, then adducts to a neutral position relative to the pelvis until the foot strikes, and then the hip is rapidly adducted (as the foreleg) during the first double support, while the unilateral hip is rapidly abducted (as the hindleg) during the second double support [32]; and 3) internal and external rotation: internal rotation of the unilateral hip begins terminal swing and continues through stance until the contralateral foot strikes [32].

During SW, there are varying degrees of hip flexion; however, in general, the hip presents with slight flexion. At late DFL, when pelvic movement is completed and the COM has been moved to the contralateral foreleg, the unilateral hip and knee are flexed rapidly along with the pelvic tilt, the toe is off; and the unilateral leg begins to dangle forward until the foot lands. During COMT, both hips show a slight abduction. The pelvis is naturally inclined during early and late DFL. The lower side of the pelvis presents relative abduction, whereas the other side presents adduction. However, both abduction and adduction are caused by gravity rather than muscle action. The pelvis also has a natural lateral inclination during SFL (dangle phase). Slight abduction of the hip on the lower side of the pelvis is caused by the action of the abductor, whereas adduction on the other side is not caused by the action of the adductor. During the initial COMT, slight external rotations occur at both hips and continue at mid-COMT until the final COMT. External rotation is stopped, and internal rotation occurs with anterior pelvic rotation. At the late DFL, the contralateral foreleg and hip are stable, and the unilateral pelvis rotates forward until it faces forward (at which point the flexion of the unilateral hip is relatively small).

(2) Knee posture

The movement of the knee shows flexion and extension in the sagittal plane. In the NW, knee flexion and extension alternate. For the support leg, in this stance phase, the knee is first extended, then flexed, and then extended again before the final flexion [34]. That is, before midstance, the knee enters an extended state, followed by knee flexion [34]. In the mid- and terminal swings, the knee is nearly fully extended to prepare for the heel strike [38]. In mid-swing, owing to the slight flexion of the support leg and slight inclination of the pelvis, the swing leg becomes relatively too long to leave the ground, and the flexion of the knee joint of the swing leg can produce this gap [34]. In the SW, the knees are flexed to a certain degree. During the COMT, both knees remain slightly flexed. While entering the late foreleg weight-bearing/standing (DFL) position, the hindleg immediately increases the range of knee flexion, raising the heel of the hindleg until toe-off, and begins to dangle forward (early dangle). The greatest flexion occurs at mid-dangle. When the swinging leg passes through the support leg, the length of the swinging leg becomes relatively long because the knee of the support leg is slightly flexed and the pelvis is tilted to a large extent. To avoid dragging the foot to the ground, the knee of the swinging leg requires large flexion. Knee flexion in SW differs from that in flat-trajectory walking proposed by Saunders et al. [67]. The knee of the support leg of the former was slightly flexed throughout the walking process. During COMT, the COM smoothly transitions from the hindleg to the foreleg in the horizontal plane, and the COM does not rise or fall owing to the leg dangle. The latter is achieved by deliberately flexing the knee of the support leg to avoid COM elevation, which results in greater muscle activation, muscle strength, and metabolic costs [68-70]. From the late dangle to the early DFL, the hind support leg is always slightly flexed, and the flexion amplitude of the swing leg is reduced (caused by gravity) in the swing forward from the support leg side to help the physiological prolongation of the leg. However, the knee remains slightly flexed at the moment of landing.

(3) Ankle posture

In NW, when the heel strikes, the ankle is in a neutral position, and the GRF is located behind the center of the ankle, resulting in plantarflexion [32]. Toward the end of a unilateral single stance, the heel begins to rise as the plantar flexors increase their contractility and concentric action [71, 72]. At the opposite foot strike, the ankle that was about to leave the ground lost some dorsiflexion but did not return to neutral. At foot-off, fast plantar flexion can reach a maximum [32]. Electromyography has shown that unilateral plantar flexors are silent after an opposite foot strike [71, 72], indicating that unilateral plantar flexion occurring after the opposite foot strike is passive [32]. Rapid dorsiflexion of the ankle occurs when the foot begins to swing, and plantarflexion occurs again when the foot strikes the end of the terminal swing [32]. During SW, in most cases, the ankle presents with slight dorsiflexion of the calf slightly tilted forward, accompanied by slight flexion of the knee. Plantar flexion of the ankle mainly occurs when the heel of the hindleg is raised from late DFL to early dangle and when the forefoot lands from late dangle to early DFL. However, plantar flexion during these two stages was not active. Plantarflexion of the hindfoot is caused by the raised heel owing to knee flexion, whereas plantarflexion of the forefoot is caused by gravity as the muscle relaxes. A larger active dorsiflexion occurs during the mid-dangle phase, creating a gap between the swing
foot and the ground.

(4) Foot posture

In NW, the foot rotates externally, starting from the contralateral foot-off, whereas the foot rotates internally in preparation for foot contact at the terminal swing [32]. There is an internal rotational motion between the contralateral foot strike and foot-off (during the second double support) [32]. During heel landing in SW, the foot is mainly upright, which is in a state of slight foot adduction (toe forward) and inversion under the condition of slight knee flexion [31]. The toes are kept forward throughout the walking process.

2.4.3 Upper-limb posture

In the NW, accompanied by thoracic and shoulder rotations, these rotations are opposite to pelvic rotations at moderate walking speeds [34]. However, shoulder rotation is less common than pelvic rotation [73]. Shoulder rotation leads to the swing of the arm [34]. Without limitation, the arms tend to swing in a direction opposite to that of the lower limbs [33]. That is, the forward swing of one leg is accompanied by the forward swing of the contralateral arm [34]. During SW, the COM is always placed in the BOS, and the body does not tilt forward and backward as well as sway left and right like an inverted pendulum. Therefore, the body is relatively stable without the need for an arm swing to maintain balance. However, the arms also swing slightly when walking owing to the inertia caused by the acceleration and deceleration of the trunk with the rotation and movement of the pelvis during COMT.

3. Conclusion

There are essential differences between NW and SW in terms of gait events, movement modes, COM activities, and dynamic postures. During NW, the heel strikes and the toe pushes off, and the body tilts forward and backward in the sagittal plane, sways from side to side in the frontal plane, and moves vertically upward and downward. The COM is always located outside the BOS during single support (swing phase). The trunk and pelvis are moved inversely. The shoulders rotate with the trunk and drive the arms to swing. The hips and knees are alternately flexed and extended. In SW, the forefoot lands without striking because the COM is located on the hindleg and the hindfoot is off the ground without pushing off. The body moves horizontally in the sagittal and frontal planes, and COM motion is always located in the BOS. The trunk remains vertical and moves synchronously with the pelvis. The shoulder does not rotate, and the arm moves with inertia. The hips and knees are slightly flexed.

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Author Contributions

LM, as the creator of sitting-walking, contributed to the design, implementation, and establishment of the theoretical system, as well as the conceptualization and writing of the manuscript. LJZ was involved in the overall practical operation and experience and provided technical suggestions on the manuscript content. All authors (LM and LJZ) have read and approved the manuscript.

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