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Sitting-walking Derived from Tai Chi Gait: A Fundamental Improvement to Fall Prevention in Older Adults (Part 2)—Advantages of Sitting-walking

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Abstract

Humans have never questioned the unique normal walking (NW) pattern they rely on for survival. Even if instability or falls occur during walking, people do not attribute the problem to their walking pattern, but rather to their physiological (including psychological) factors. A significant body of literature primarily emphasizes individual physiological (including psychological) aspects when addressing fall prevention in older adults. It seems that the NW pattern is perfect. However, this is not entirely the case. Aiming to address the phenomenon of human instability or falls during walking, after years of observation and exploration, the authors discovered that the primary cause of instability or falls during walking mainly originates from issues within the problems existing in the NW itself. In response, the authors propose a sitting-walking (SW) mode derived from the Tai Chi gait. The long-term practice has confirmed the uniqueness of SW in maintaining gait balance. In this paper, by comparing NW with SW, the problems associated with NW and the uniqueness of SW will be discussed. The main problems of NW and its negative effects on walking stability and the body are discussed, focusing on gait, balance, and posture. At the same time, according to the characteristics of SW (described in the first part), the paper introduces the advantages of SW in terms of walking stability while effectively avoiding the related problems of NW.

Keywords

Problems existing in normal walking, cause of instability or falls during walking, gait, balance and posture, advantages of sitting-walking

Introduction

Human walking is a relatively unique form of bipedal walking, and although there are other bipedal animals (bears, primates, and marsupials), human walking is an efficient and functional form of walking [1]. That is to say, most people walk fairly easily, and surprisingly efficiently [2]. For ordinary people, walking is not technically difficult; on the contrary, it is almost easy. The seemingly inescapable conclusion, then, is that each of us has learned to integrate into a smoothly operating whole the numerous variables that nature has endowed with our neuromusculoskeletal systems [2]. It can be said that humans are currently unparalleled in bipedal walking [3]. So, is this movement that humans take for granted perfect? Unfortunately, this is not the case, and the human gait pattern is flawed.

Walking in humans as bipedal provides the central nervous system (CNS) with a particularly challenging balancing task that is very different from the balancing task when standing [4]. According to the definition, standing balance (or static posture control) refers to the ability to maintain the body's "immobility" in a given environment and position, that is, to stabilize and minimize the movement of the center of mass (COM) [5, 6]. The balance task of standing is to safely maintain the body's COM within the base of support (BOS) [4]. The COM corresponds to the point where the whole body's mass is concentrated, which is the application point of the gravity vector [7]. In a standing position, a BOS is an area that includes each point at which the foot (or both feet) touches the support surface [7]. When a person walks, the task suddenly changes [4]. The goal of walking is to move the body outside the BOS while preventing falls [4]. That is to say, the body moves forward by changing the position of the COM. In this case, when one wants to take one or more steps off the ground balance changes dramatically [4]. The state of balance at this point is described as dynamic balance, which means that the swinging limb has a trajectory that will reach the condition of balance in the next stance stage [4]. Specifically, walking begins by leaning forward, and to prevent falling, instantaneous balance is achieved by moving either foot forward to a new position [8]. Therefore, walking can be defined as a series of alternating processes of loss and restoration of balance [8]. Gait can be defined as a movement that involves the translation of the entire body, allowing the movements of body parts to be repeated while maintaining balance [9]. However, the transition from standing to walking is not a trivial event [10]. It is during walking that humans pose the biggest challenges to their systems: initiating and terminating gaits, turning, avoiding obstacles, and bumping into people and objects [4]. Therefore, balance control is a challenging task for bipedal humans because the large mass (2/3 of body mass) of the head "arm" and trunk (HAT) based on a relatively small BOS are located at considerable distances (2/3 of body height) [11]. Thus, the human body is an inherently unstable system unless its control system continues to act [4]. The concrete manifestation of this instability in walking is imbalance and even falling. Falling while walking is a major health risk for older adults [12].

It is a common problem in walking that ordinary people (especially older adults) are prone to imbalance and falls during walking, especially when they encounter interference. Why does this happen?

After years of observation and research, the authors have concluded that the normal walking (NW) gait pattern of ordinary people, whether young or old, is the root cause of imbalance and falls.

So, what is the problem with the human NW pattern? What are the negative effects of this problem on walking (especially for older people)? Is there a solution to this?

There is a scientific aphorism, as cited in Childress and Gard [13], stating that "It had been seen many times before but never observed (p.21)." This phrase is most appropriate in the discussion of the problem of human walking. The problem with human walking is that its defects are rarely questioned.

The authors believe that the purpose of walking is to move the whole body forward through the movement of the body. At the same time, the task of the limbs in the process of walking is to maintain the balance of the body, which largely depends on the walking posture. The posture has three main functions: (1) anti-gravity function; (2) positioning of the body relative to gravity; and (3) the adaptation of posture to body spatial positioning [14]. In all unpredictable and changeable situations, a powerful and flexible posture control system is needed to survive [15]. Posture control is considered to be a complex motor skill, which stems from the interaction of multiple sensorimotor processes [16]. While the neural control of postural orientation and balance involves most of the nervous system and all parts of the body, the postural system is often forgotten because it usually operates at an automatic, involuntary level [15]. This is why humans have posture problems all the time without even realizing it. The author provides a detailed discussion on the issue of posture in the book *Tai Chi Medication*. It can be said that the posture of walking determines the balance of the body, which in turn determines the stability of the gait. In other words, improper walking posture will first affect the balance of the body and affect the gait of walking, thereby affecting walking activities. From this point of view, walking gait, balance, and posture are the three important factors of walking, of which posture is the key element.

There are problems with gait, balance, and posture in NW patterns. These problems are particularly prominent in the walking activities of older adults and are also the key reasons for their falls. Based on Part I, this paper will discuss the problems existing in the gait, balance, and posture of NW. By comparing two walking modes, this paper qualitatively describes how these problems in NW can be fundamentally avoided in SW reflecting the unique advantages of SW.

1. Comparison of gait stability during walking

1.1 Gait in NW

In NW, human walking is initiated by leaning forward of the body [8]. Specifically, it is the forward inclination of the trunk. Gracovetsky [17] points out that the trunk is the main initiator of gait, which promotes movement. Researchers generally conclude that a small amount of trunk movement occurs during the gait process [18-21]. It has been shown that there is a repeatable sequence of trunk movements during gait [18, 22]. This movement occurs in three dimensions. In the sagittal plane, there are two movements (forward and backward) oscillations of the trunk in a gait cycle [18], which are described as leaning forward or backward [23]. Moreover, like an inverted pendulum, the COM of a human walker rises and decelerates in the first half of the standing phase, then falls and accelerates during the second half of the standing phase [19, 24-26]. That is to say, in the vertical direction, there are also rising and falling motions. At each step, the body decelerates and then accelerates again because the support provided by the legs is not always kept directly below the body [2]. There is also a predictable pattern of frontal movement during gait [18, 21, 22], which is described as the trunk moving towards or away from the standing limb [23]. At the heel strike, the trunk moves toward the standing limb and reaches its maximum magnitude at the contralateral toe-off [18, 21, 22]. Therefore, the movement pattern of the frontal plane is inclined toward the side away from the supporting leg. Because two-thirds of the body mass (head, arms, and trunk (HAT)) is located at two-thirds of the height above the ground, this inverted pendulum is inherently unstable when considering the forward momentum of HAT and the movement of the COM away from the supporting leg during single support [4]. As a result, it can be seen that the NW gait presents an unstable state of up and down, forward and backward, and swaying from side to side. This instability can easily cause imbalance, causing every step of walking to tend to lean forward, backward, and sideways [27]. From this point of view, NW can be visually seen as a falling-walking [27].

1.2 Gait in SW

In contrast, during the whole process of SW, there is no movement of ups and downs, leaning forward and backward, or swinging from side to side. The forward horizontal movement is shown in the sagittal plane, while the side-to-side horizontal movement is shown in the frontal plane. In the process of COM movement during the COM transformation (COMT), because the COM is always within the BOS of the supporting leg, coupled with a large pelvic tilt, the swinging leg is closer to the supporting leg, and the relaxation of the hip muscles results in a physiological extension of the swinging leg [27]. Therefore, the landing position of the front legs will not deviate greatly in the transverse plane, and the movement of the body COM in the frontal plane is relatively small. When landing on the front foot, the COM can still be maintained within the BOS of the rear support leg, keeping the body in a stable state. If NW is likened to an upright triangle rolling on a horizontal plane, then SW is like a ball rolling on a horizontal plane [27].

2. Comparison of body balance during walking

The fact that humans, as bipedal animals, move on the ground in the form of one-foot contact (walking), no-foot contact (running), or two-foot contact (standing) poses a major challenge to the human balance control system [4]. Balance is defined as the ability to control the COM relative to the BOS [28]. The loss of control of the COM means a loss of balance, resulting in a fall. This indicates that the positional relationship between COM and BOS is important for falls [29-31]. Walking can be divided into three stages: gait initiation (GI), stepping, and gait termination (GT). The movement of the body COM during NW and SW is different in these three stages, resulting in correspondingly different manifestations of the body's balance state.

2.1 Balance during stepping

During the stepping of NW, the change of COM is mainly reflected in the deviation of the sagittal plane and frontal plane. To accelerate the COM in the forward direction, the walker must actively begin falling forward to accelerate the COM ahead of BOS [4]. The COM rises and falls respectively in the first and second half of the stance phase [19, 24-26]. Thus, in the sagittal plane, the body appears to lean forward and backward. When the trunk leans forward, the body’s COM is located on the front side of the support foot; When the body leans back, the body’s COM is located behind the support foot. At the same time, along with the ups and downs of the body, the body’s COM rises and falls in the vertical direction. Therefore, in the sagittal plane, the body's COM shows a trajectory similar to a parabola or "sinusoidal curve" [8] from back to front in the process of initial swing, mid-swing, and terminal swing. In the frontal plane, the body's COM is never located directly above the body's BOS during single support [8]. Once the stepping begins, the COM can be seen moving forward along the inside edge of the support foot [4]. This means that in steady-state walking, COM remains outside the BOS (except for the brief double support period during walking) [4]. Therefore, walking is a multi-dimensional activity with significant lateral movements

[32]. This fact shows the relative imbalance of the body during gait, especially in the process of single support when the foot must be positioned slightly lateral to the vertical projection of the body's COM to control its side-to-side movement [8]. Therefore, in NW, the COM is always located outside the BOS and tends to tilt towards the opposite side, resulting in a state of side-to-side swaying, which is also the key to instability and easy imbalance. Although re-stabilization can occur during two short double support periods, the support foundation is not very strong during this period (one foot receives weight on a small area of the heel while the other foot is pushing off on the front half of the foot) [4].

In the process of SW, the COM is placed within the BOS at any time, and there is no fluctuation in the vertical direction. The movement in the sagittal plane and frontal plane is horizontal, and the side-to-side movement amplitude of the frontal plane is relatively small. The movement of the COM occurs during the COMT of a double-foot landing (DFL), and the BOS area is relatively large. Therefore, the body's stability is good and the balance is easy to control.

2.2 Balance during gait initiation

The GI of NW is a transition from a stable static balance to a continuously unstable gait, which is a challenge to the balance control system [33]. Because the feet are side-by-side before GI, the initial swinging limb is unable to produce the "push-off" energy common in steady-state gait [34]. Therefore, the energy for the first step must come from other sources, including passive gravity forward-leaning and active hip flexor contractions to pull the swinging leg forward [34]. During GI, balance is disturbed because the action of lifting the swinging foot off the ground creates a gap between the COM and the center of pressure (COP), which is what causes the body to be unbalanced and fall toward the swinging leg side [35]. As a result, stepping forward with a swinging foot can lead to a potential lateral imbalance [35]. GI begins with a lateral movement of COM, which, if too lateral or too fast, can cause a loss of balance, possibly resulting in a fall [36, 37]. GI poses a challenge to COP and COM control [38, 39]. Mechanically, one of the key features observed during moment generation and GI is that the COP moves from anterior to posterior direction before the first step, resulting in assisted fall-like behavior of the COM [40-42]. Therefore, due to the transition of the whole body's COM from a large BOS to a small one (from biped to monopod position related to gait), GI, as a functional task, represents one of the first spontaneous unstable behaviors in the development of motion patterns [43].

By contrast, the GI of SW is not the case. During GI, in the standing state, the hips are first relaxed, the pelvis is tilted to the side of the swinging leg to place the COM in the BOS of the support leg, and then the hip flexors are slightly contracted to bring the swinging leg forward to the ground (early DFL). During this process, the COM remains stationary and is placed inside the BOS along with the COP, so there is no tendency for the body to tilt laterally. Subsequently, the pelvis on the hind leg side descends (initial COMT), while the back heel pushes the ground to generate forward kinetic energy. At the same time, the COM shifts with the rotation and the lateral inclination of the pelvis towards the front leg until it moves into the BOS of the front leg. During this process, the pelvis and trunk remain upright and there is no tendency to fall forward. Thus, it is a steady GI.

2.3 Balance during gait termination

During the GT of NW, a walker transitions from a stepping to a standing posture. This process is characterized by an increase in braking force on the front foot and a decrease in push-off on the back foot during the final step [44, 45]. The key difference between GT and gait movement is that the propulsive phase is weakened [39, 46]. Gait termination is a transient phenomenon that requires bi-directional adjustment of ground reaction forces (GRF) through coordination between limbs to accelerate and decelerate, thereby stopping forward momentum and dissipating kinetic energy [47-49]. Therefore, GT also poses a challenge to COP and COM control [38, 39]. For GT, the COP is forward and lateral of the COM by toe-off of the last swing limb [40]. This causes the body to show an unstable tendency to fall backward and laterally due to the toes of the swinging legs being off the ground. However, during this process, it also causes COM to rapidly decelerate in the forward direction and generate medial acceleration [40]. The forward movement of the body must be slowed down to achieve a safe GT and stable upright position [47, 50]. At this point, the COP quickly moves to the back, closely aligned with the COM [40]. Only in the final bipedal standing position, the COM coincides with the COP at the BOS [51, 52]. A descriptive study of GT illustrates the interaction between the COM and the COP during the termination phase [40]. The study concluded that coarse control is achieved through foot position during GT [51]. Therefore, foot position is the key to GT [47]. That is to say, only by placing the swinging foot safely can falling at each step be avoided [4]. However, it is important to note that the termination strategy depends on the gait velocity and whether the termination is planned or unplanned [49]. Planned GT (PGT) and unplanned GT (UGT) have different patterns of movement and muscle recruitment [39]. Since GT is associated with the rapid deceleration of the forward momentum of the body and complex interactions of the neuromuscular system, feed-forward neuromuscular control and reactive motor response to external stimuli may be challenged [53]. PGT challenges feed-forward while UGT challenges neuromuscular feedback control [53, 54]. PGT, a stable and non-novel activity of daily living (ADL) task, challenges the posture control system and relies on active feedforward control [55]. Mechanically, two coupled braking mechanisms are required at PGT: 1) reducing foot propulsion during the penultimate step and 2) increasing braking force during the terminating step [39]. When people are forced to undergo UGT, the urgency of spontaneous activation of dynamic stability increases [56]. Therefore, compared to PGT, the human body needs to increase braking force and decrease thrust for a short period to generate sufficient net braking pulses during UGT [57]. That is to say, if the walker has to stop quickly, the risk of falling should be particularly high [47]. It should be said that because the body's COM is behind the support leg in the push-off stage of the back foot, the body still has the potential to fall backward, so the process of push-off must obtain the kinetic energy to push the COM forward and upward. At the same time, the COM must return to the BOS for the body to achieve stability. In short, stability requirements must be met to achieve safe GT [43]. As a result, balance is challenged in the transition from one statically or dynamically stable mode of motion to another [39].

In the GT of SW, the movement mode is completely different from that of NW. For PGT, in the initial COMT, the kinetic energy is reduced by weakening the back pedal force to slow down the movement of the COM. In this way, when entering the late DFL, the kinetic energy (KE) will not be very large, and a slight action of the hip extensor muscle can make the swing leg land on the support leg side. For UGT, there are three terminating situations: Firstly, it occurs during the dangle phase. As the COM is always within the BOS of the support foot, the body is in a balanced state, and the swing leg can end the swing and land on the ground at any time to terminate the gait. Secondly, it occurs in the COMT. Although KE is generated in this process, the pelvis is also in motion, but because the feet land on the ground, the center of mass is located in the load-bearing base with a relatively large area, the body is stable, and the gait can be terminated by stopping the pelvic movement at any time. Thirdly, it occurs in the early DFL. This is a sudden GT when the swinging leg just lands on the ground. At this point, as the COM is still located on the rear support leg, the front leg can be retracted to achieve GT. Although the COM and the COP do not coincide during the COMT, the trunk remains upright and there is no tendency to tilt, so the KE and velocity generated during the COMT do not affect the balance. In other stages, both the COM and COP are located within the BOS, resulting in a small impact of rapid GT on balance.

In summary, as stated in the author's book, the two walking modes reflect different balance modes [27]. During NW, the body is constantly in an alternating process of imbalance and balance, and the stability of the body is characterized by imbalance when supported on one leg and balance when supported on both feet, resulting in an intermittent or alternating balance pattern; During SW, regardless of whether it is a single-leg support or a dual-leg support process, the body is always in a balanced state, so it is a random balance pattern [27].

3. Comparison of body posture rationality during walking

Dynamic posture changes can change the position of the COM [1]. During walking, the body's COM, although not kept in a fixed position, is often kept within the pelvis [2]. Specifically, the COM of the entire body is within the trunk at the second sacral vertebra (S2) level [58]. Therefore, the issues of COM are closely related to the trunk. In other words, the dynamic posture of the trunk plays a decisive role in the movement of the body's COM. Although the range of motion is small, the trunk plays an important role in human movement [59]. In particular, the trunk plays an important role in posture control to ensure the successful execution of functional activities such as gait [19, 60]. Gracovetsky [17] proposes the theory that the trunk was the primary engine of human movement. Trunk Kinematics is critical to maintaining body balance [19]. The main function of trunk movement is to balance the asymmetric movements of the lower limbs [61]. In terms of the pelvis, several authors emphasized the importance of pelvic movement in human gait [62, 63]. The pelvis plays a crucial role in normal gait by effectively controlling the motion of the COM [64]. That is to say, pelvic motion during gait helps optimize the motion of the COM, resulting in smooth and efficient motion [65]. This pelvic vertebra called by Dubousset et al. [66] forms the bond between the trunk and the lower limbs. Walking mainly involves the movement of the lower limbs. For the lower extremities, the kinetic chain of the multi-segmental system is connected with the movements of the hip, knee, and ankle joints [57, 67]. Leg movements provide the foundation for balance and stability [68]. This indicates that the dynamic posture during walking is based on the trunk posture and affects the COM through the movements of the pelvis and lower limbs, thereby affecting balance.

3.1 Trunk posture during walking

During stepping in NW, in the sagittal plane, there were two oscillations that occurred during the gait cycle: maximum trunk flexion occurred at heel strikes, while maximum trunk extension occurred at single leg support [22]. That is to say, the forward and backward tilt of the trunk relative to the vertical direction are both prominent [60]. Frontal movement is described as the trunk toward or away from the stance limb [17]. It is manifested as alternating tilting towards both sides. In the GI of NW, it consists of two consecutive stages: the first phase of the anticipatory postural adjustments (APA), with the trunk leaning forward, similar to a controlled fall, precedes the second phase [69]. APA helps the body's forward progression [70], which occurs before the initial swing of the leg at GI [71]. Nevertheless, GI is a functional task that represents one of the first spontaneous unstable behaviors during the development of motor patterns [43]. During the GT phase, there is still a problem with the trunk leaning back. The ability to maintain a 'static' posture after the foot reaches its final position is also required for GT [72]. This means that, in terms of PGT, adequate control of the upper body must be maintained to prevent loss of balance [72]. During UGT, the ability to quickly and effectively execute GT tasks to respond to unknown stimuli is very important [73]. The results of failure are often falling or more serious injuries [74]. However, during the GI and GT, as well as stepping, any single leg support will be accompanied by lateral tilt. The inclination of the trunk in the sagittal plane and frontal plane is an unstable factor. This may put people with sensory or motor impairments or disorders at risk of falling [75-77].

During SW, trunk posture is considered the primary task. Throughout the entire SW process, including the GI, stepping, and GT stages, the head, neck, and trunk remain upright. Most researchers believe that the lower extremities drive human movement, while the trunk primarily serves as a stabilizer [22]. It can be said that the trunk provides a stable base for extremity movement [78]. Therefore, adequate control of the trunk related to extremity movements is essential for effective and stable movement [18]. It is important to actively control the body's verticality in the sagittal and frontal plane to stabilize the head containing visual and vestibular sensory references [79]. The three main sensory systems, namely the visual, vestibular, and somatosensory systems, are related to balance and posture [4]. The stability of posture, the accuracy of head orientation, and visual balance depend on the connection between vestibular, visual, and proprioceptive afferent information [80,81]. Llinás [82] argues that the "center point" of vestibular system activity regulation is based on the vertically upright body posture (p.216). This "center point" is described as the level at which most neuronal receptors operate for a given sensory pattern [82]. This emphasizes the importance of vertical alignment of the head and trunk as the center point and is evidence supporting the alignment principle of Tai Chi, which states that the head is suspended above and the trunk remains vertically upright [83-85]. However, the nervous system controls posture via the interpretation of vestibular input through somatosensory input [15]. Visual input can provide information about the direction and speed of the body swing as well as confusing and vague information about the movement of the body's COM [15].

In addition, research reports suggest that compared to trunk vertical gait, greater impact force and 22% higher load rate are associated with forward flexion of the trunk [79]. Therefore, maintaining a vertical trunk can also reduce the force required to support the entire body's COM and promote coordination between the upper and lower segments [79]. Given this, the vertical posture of the trunk used in SW plays a decisive role in maintaining walking balance. This posture is neither disturbed nor affected by lower limb activity.

3.2 Pelvic posture during walking

The adaptation of modern human pelvis to habitual bipedal movements has led to specific pelvic movements during walking [65]. In general, the motion of the pelvis is described as a rotation around one of three main axes, each of which produces motion in one of the planes [86].

3.2.1 Pelvis posture in the transverse plane

During NW, in the transverse plane, a similar pattern of GI and stepping is observed with a single oscillation occurring once per cycle in the upper and lower trunk rotations that are almost opposite in phase [87]. That is to say, the opposite phase rotation occurs between the upper and lower trunk in the transverse plane [88, 89]. Therefore, the pelvic angular momentum is balanced by rotating the thorax in the opposite direction or by swinging the arms [90-92]. If the pelvis rotates under a relatively stationary body, the lumbar spine rotates or twists in the opposite direction to the rotating pelvis, the limited rotation mechanism of the lumbar spine limiting the rotation angle [93]. In theory, a 3º axial rotation in any lumbar intervertebral joint will damage the articular surface and tear the collagen fibers in the annulus [94]. Therefore, this reverse rotation does not conform to the physiological mechanism of the lumbar spine [27]. Additionally, the pelvic rotation has the function of increasing stride [95]. During the mid to late swing, the forward rotation of the pelvis (with the swing side ilium in front and the support side ilium in back) causes the COM to deviate more forward from the support leg based on the trunk's forward tilt, thereby increasing the unstable tendency of the forward tilt. Furthermore, in NW, an increase in speed can lead to an increase in pelvic rotation [96, 97]. This increases the amplitude of rotation and forward-leaning between the upper and lower torso, thus further reducing body stability.

During SW, the pelvis undergoes transverse rotation only during the COMT phase, and the shift of the COM also occurs at this time. When the COMT ends to enter the late DFL, the rotation of the pelvis and the shift of the COM also end. At this point, due to the internal rotation of the support leg at the hip, the pelvis stops rotating forward and ends in a position facing straight forward until the next COMT. During the dangle phase, the COM is always located in the support leg and is not affected by the swing leg, which avoids the forward shift of the COM. In addition, throughout the SW process, regardless of whether the pelvis is rotated, the trunk and the pelvis are always synchronized and kept upright, and the upper and lower trunk are as one, so there is no rotation and twisting in the lumbar vertebrae.

3.2.2 Pelvis posture in the sagittal plane

During the entire NW process, the pelvis tilts back and forth [86]. Nevertheless, in the sagittal plane, the pelvis usually keeps the pelvis tilted forward throughout the gait [98]. The forward tilt of the pelvis in the sagittal plane causes the lumbar spine to appear lordotic which causes the sacrum to tilt and the fifth lumbar vertebra (L5) tends to slide forward on the sacrum. In this area, the only structures that can maintain the L5 vertebral body on the sacrum and limit slip are the lumbosacral intervertebral disc and paravertebral muscles [99]. Therefore, during NW, the paraspinal muscles will continue to undergo isometric contraction. The hip extensor muscles participate in trunk extension movements [100], are in a state of tension, and tend to fatigue at the same time as the paraspinal muscles [101]. Fatigue is most likely to increase the stiffness of the hip extensor muscles [102]. This makes the trunk and hips rigid throughout the gait (the body is like a stick) making it easy for the body to be out of balance in the face of external interference. Fatigue of the hip and back extensor muscles can affect both reactive balance control and lumbar stability [103]. Since the body's COM deviates from the BOS and is located at its rear and front sides respectively at the initial and terminal swing with a single support, and there is a gap between the swing foot and the ground, it shows an unbalanced trend of falling backward and forward in the sagittal plane. In addition, pelvic forward tilt can also affect the amplitude of pelvic lateral tilt in the frontal plane.

During SW, the pelvis is vertical in the sagittal plane, the waist is in an erect lumbar (upright lumbar) posture, and the hips are slightly flexed, which significantly reduces the amplitude of pelvic forward tilt and lumbar lordosis. This not only avoids the fatigue of low back muscles and hip extensors but also makes the pelvis and hips more flexible which ensures the stability of the waist and greatly reduces the interference of leg activities on the trunk. At the same time, this also makes the trunk maintain vertical during walking without tilting forward or backward, greatly improving the stability and balance control of the trunk.

3.2.3 Pelvis posture in the frontal plane

During NW, the lateral tilt in the frontal plane mainly occurs in the single support stage. Pelvis lateral tilt can cause the mediolateral excursion of the COM, but very little to the reduction of the vertical excursion [104]. The peak of pelvic tilt occurs just after the foot-off, corresponding to early single support [1]. However, during the mid-stance, the pelvis is almost horizontal [95]. Due to some distance between the hip joint and the midline of the body, the pelvis tends to rotate away from the supporting side during single-leg support [105]. This places the body's COM on the inside of the body with a greater deviation from the BOS. Therefore, to maintain mediolateral balance, this rotation must be counterbalanced by opposing forces on the pelvis generated by the hip abductors (gluteus media, gluteus minor, and tensor fascia latae) to change the direction of the body's COM [105]. The contraction of the hip abductor muscle inevitably causes tension in the hip and limits the amplitude of pelvic lateral tilt which will also lead to a larger gap between the swing foot and the ground at the terminal swing, increasing the tendency of the body's lateral tilt. This is also the reason why the body swings from side to side. At the same time, it will also increase the ground reaction force (GRF) generated by the heel strike. In addition, during the forward step, the shift of the body to the stance or the swing limb causes a change in the horizontal position of the COM, affecting the duration of the GI [106].

During the whole SW, the lateral tilt of the pelvis has a great effect on walking. During GI, the pelvis is initially tilted to the side of the dangling leg to keep the COM within the BOS of the support leg, which ensures body stability. The transformation of the COM, during the COMT, is achieved through the lateral tilting motion of the pelvis. However, during the transition from the late DFL to the dangle phase including the whole dangle phase, the pelvis remains laterally tilted and the knee remains slightly flexed, so the COM does not rise.

This is different from the flat-trajectory walking proposed by Sanders et al. [64], which involves increasing the stance leg flexion [107, 108] to minimize the deviation of the COM in the vertical direction. During the double support phase, the two limbs act in opposition to each other [109], and support weight is achieved by bending the knee to produce greater muscle strength [107,108], causing a double metabolic cost [109].

As mentioned earlier, the pelvic lateral tilt contributes to the mediolateral excursion of the COM [104], which helps to control the lateral displacement of the body. In walking, this lateral displacement can be increased by separating the feet and decreased by keeping the feet close to the plane of progression [2]. Due to the significant lateral inclination of the pelvis during SW, the COM is in the state of minimal lateral shift and is located within the BOS of the support leg, with the two feet closer to each other in the frontal plane and the lateral displacement of the body relatively small. Furthermore, pelvic tilt contributes to the effectiveness of the hip abductor mechanism (abductor muscles and iliotibial tract) [2]. The pelvic tilt during SW is based on the relaxed state of the hips which also causes physiological extension of the swinging leg, making it easier for the swinging foot to land in the late dangle phase. In addition, with a large lateral tilt amplitude and the COM always kept within the BOS of the support leg, the GRF generated by swinging foot landing on the ground during slow walking can be ignored, and the GRF generated during fast walking is also relatively small.

3.3 Hip posture during walking

During NW, the movement of the lower limbs always experiences stiffness at different stages. Lower limb stiffness is related to the extension of the hip joint, which occurs during the transition from the double support to the swing phase. From foot-flat to toe-off, the hip of the leg is extended [110]. Hip extension causes tension in the hips and increases lumbar lordosis. The lumbar muscles must generate power to maintain a rigid posture of the trunk to prevent the COM from collapsing. In addition, when the hip joint moves into extension, all three major hip joint ligaments (iliofemoral, ischiofemoral, and pubofemoral) will tighten [104]. Therefore, continuous walking can easily cause fatigue in the paraspinal muscles, hip extensors, and hip ligaments. As a result, a hip extension can cause stiffness in the trunk and leg. A stiff leg has poor flexibility, resulting in a smaller range of motion, which is itself a known risk factor for falls [111, 112].

During SW, the hips are always in a slight flexion, which not only does not interfere with the pelvis but also does not increase the lumbar lordosis. This reduces the load on the hip extensor, lumbar extensor, and hip ligaments, and also increases leg flexibility and trunk stability.

3.4 Knee posture during walking

During NW, the knee joint undergoes two knee extensions in one gait cycle. One occurs before the mid-stance when the knee joint is extended [2]. The gradual increase in knee joint extension during the single support process leads to a significant increase in COM vertical displacement [34]. This is another reason why the body rises and falls in the vertical direction when walking. Another one almost complete knee extension is done before the heel strike [1]. That is, knee extension occurs at the end of the terminal swing which will continue until the moment of initial contact. The impact of the swing foot on the ground will produce a large peak vertical GRF [35]. This not only negatively affects the leg and trunk tissues, but also causes slipping.

3.4.1 Effects on body tissue

A peak vertical GRF produced by the collision between the swinging foot and the ground is transmitted from the swinging foot to the whole body through the bones and soft tissues [35]. This peak, the slope of the vertical GRF rise after the swing foot contact, may potentially cause discomfort or pain to the body joints during repetitive tasks [113, 114]. The lower extremities, especially the skeletal tissues, will be subjected to the corresponding force generated by the high and rapid impact peak of vertical GRF [113]. This high and rapid loading rate is potentially harmful to skeletal tissue, especially the bone, because of the increased hysteresis, resulting in structural damage to the tissue that accumulates in repeated events [115].

3.4.2 Disturbance to trunk

During heel strike and toe-off, the strong contact between the foot and the support surface affects the movement of the pelvis, which leads to oscillations affecting the phase progression of the pelvic rotation [116]. The GRF generated by the heel strike is transmitted to the trunk through the lower limb and pelvis, which tends to flex the trunk forward as the body's COM is relatively located forward [58]. A forward-falling tendency occurs as the COM falls forward at the terminal swing. Forward flexion of the trunk should be avoided to maintain balance. The GRF causes the trunk muscles to react during gait [58]. Therefore, at heel strike, it seems that the activity of the back extensor muscles resists trunk flexion [58]. This makes the trunk stiff, accompanied by tension in the hip extensor muscles, causing the entire body to stiffen. As a result, during walking, it is easy to lose balance due to difficulty in adjusting the body. If not properly balanced, these disturbances to the body caused by the GRF generated by the heel striking can be the cause of the fall [35].

3.4.3 Occurrence of slipping

The forward (and backward) shear forces generated by GRF can cause slipping. Due to the highest shear force near the heel contact (and toe-off) [117], these points are the most common sliding points [118]. The first peak of shear force (at initial contact) is considered the critical value for sliding that causes a fall [118]. Therefore, sliding during heel contact may lead to the key stage of falling [119-121]. At this point, sufficient friction force is required between the foot and the ground to prevent the foot from slipping forward. Therefore, as the step length increases and the walking speed increases, the GRF in the horizontal direction increases, and the required friction force increases. Thus, the force generated shortly after heel contact is considered to play an important role in slips and falls [118].

During SW, the knees are always in a slight flexion and the trunk is in an upright posture. And foot landing is not a heel strike. This does not stiffen the lower extremity, nor does it interfere with the body tissues and trunk. In addition, since the body's COM is located in the rear support leg from the late dangle phase to the early DFL. The vertical GRF and horizontal shear force generated by the swing foot landing are very small, and the required friction force between the foot and the ground is also very small, which greatly reduces the risk of slipping forward.

3.5 Ankle posture during walking

During NW, knee extension at the terminal swing can affect ankle posture. When the tibia tends to straighten completely around the femur, the knee joint rotates outward [93]. This is the spontaneous external rotation accompanying knee extension [99, 122]. When a foot strike occurs, the ankle is in a roughly neutral position (usually heel-first) [1]. Therefore, at the heel contact, the COP is just lateral to the midpoint of the heel [8], causing the point to be subjected to the GRF. In this way, at the foot contact, the GRF on the calcaneus generates a plantar flexion torque at the ankle and produces an eversion torque at the subtalar joint [8]. This makes the ankle and foot a plantar flexion and eversion tendency, respectively [8].

During SW, the knee is always slightly flexion, which can avoid physiological external rotation of the knee and keep the toes in a forward position, so that the heel contact point is basically at the midpoint of the heel. Meanwhile, because the heel does not strike the ground, the GRF generated is minimal. This effectively avoids the hidden dangers caused by foot eversion.

3.6 Foot posture during walking

During NW, at the pre-swing stage, the toe-off occurs under load and will also be subjected to the GRF, which will produce a great load on the first metatarsophalangeal joint. The GRF will generate horizontal shear force. Therefore, the second peak of shear force occurs later in the stance phase, just before the beginning of the toe-off phase [118]. During the terminal stance and pre-swing, the force exerted by the foot on the ground is backward, causing the body to move forward, so the GRF is forward [8]. Insufficient friction between the foot and the ground at this time often causes the foot to slide backward without pushing the body forward [8]. Since the body's COM is located behind the front support leg at this time, the body already tends to lean back. Without obtaining sufficient forward reaction force, the body may appear to fall back.

During SW, from the late DFL to the early dangle phase, the COM is located on the front support leg. The toe-off is not achieved by pushing off the ground, but mainly through the contraction of the hip flexors and the internal rotation of the pelvis. As a result, there is almost no GRF or forward-pushing force acting on the rear foot, and foot sliding is also avoided.

4. Conclusion

The problems of human NW are mainly reflected in gait, balance, and posture. The gait showed an unstable state of up and down, forward and backward, and swaying from side to side. Balance is difficult to control because the COM is always outside the BOS. The posture of the trunk tilt (forward, backward, and lateral), the pelvis anterior tilt, and the extension of the hip and knee joints during walking have a corresponding negative impact on gait, balance, and the body. Relatively speaking, SW demonstrates great advantages. The gait tends to be stable because the COM only moves horizontally in the horizontal plane, the balance remains stable and controllable because the COM is always located within the BOS, and the posture is in a reasonable state of the uprightness of the head, neck, trunk, and pelvis, as well as slight flexion of the hips and knees. These characteristics not only contribute to the stability of walking but also effectively avoid adverse effects on the body.

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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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