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Review

The difference between center of mass and center of pressure

—— A review of human postural control ——

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Abstract

This paper is a review of the relationship between the center of mass (COM) and center of pressure (COP). In the literature, there has been a major misuse of the COP, especially when it is referred to as body sway, inferring that it is the same as the COM. Careful attention is needed in the analysis of data obtained from the force platform to avoid confusing the COM and COP. We focused on the biomechanical aspects of human balance and posture, and described them while citing former studies. We clarified the definitions of the COM and COP, explained about the quiet standing using the inverted pendulum model which includes the control of the COP, and reconsidered the kinematics of gait initiation, which shows an obvious difference between the COM and COP. Our consideration is that a proper recognition of the COM and COP would be helpful in the evaluation of balance and posture by clinical therapists in the rehabilitation field, and also valuable for preventing falls in individuals with impaired postural control.

Key words: center of pressure, center of mass, postural control

Introduction

Falls are the leading cause of injuries in elderly adults. Injuries and loss of life due to falls are very serious problems common to the aging society. If we look at the epidemiology of falls, we see that about 50% of falls occur during some form of locomotion (Niino et al., 2003; Prudham et al., 1981). There is little doubt that difficulty in controlling balance is a major contributor to an increased risk of experiencing falls and sustaining fall-related injuries. In the field of physical therapy, much research on balance and posture has been performed from various aspects.

Three major sensory systems: vision, vestibular, and somatosensory systems, are involved in balance and posture. Previous studies reported that an absence of visual input has been shown to result in increased body sway that is directionally specific (Fitzpatrick et al., 1994). The vestibular systems, especially the otoliths, have the potential to measure the head's horizontal acceleration in both antero-posterior (A/P) and mediolateral (M/L) directions (Winter et al., 1998). Elimination of pressor receptors under the feet through ischemic blocking increases body sway (Diener et al., 1984). Standing or dynamic motion is a complex activity both mechanically and neurologically. In this paper, we focused on the biomechanical aspects of human balance control.

The force platform is a common apparatus used to evaluate postural control in humans. It can calculate the center of pressure (COP) of vertical loads from values of three or more vertical load sensors on a level surface (Demura et al., 2005). The force platform is often called a 'stabilometer' (Dalvin, 2004; Megrot et al., 2006; Fujita et al., 2006) as it is supposed to be able to measure body sway. Parameters of the force platform surely represent some values of body sway. However, there is confusion about interpretation of the data. A majority of researchers have erroneously referred to the COP signal from the force platform as the center of gravity (COG).

The purpose of this paper was to clarify the difference between the center of mass (COM) and COP. Integration and interpretation of the relationship between the COM and COP would aid in appropriately evaluating balance and posture.

Do force platforms really represent the abilities of balance control?

Subjects are usually obliged to stand upright on platforms in the laboratory when postural stability is evaluated. However, it is not difficult to obtain almost the same COP data on upright standing by taking an alternative standing posture. Fig. 1 shows two different postures providing an example of a similar M/L displacement of the COP. Since the fluctuation of M/L displacement in both A and B is not prominent, being almost linear, it can be said that the subjects in both A and B have good balance control. Although subject B took an abnormal posture by bending his trunk and neck laterally, he could maintain the unreasonable posture for five seconds while keeping the COP in nearly the same location in the M/L direction, as seen in the graph. We frequently see elderly patients who have kyphosis (rounded back) but also have the ability to stand still, or see patients with Parkinson's disease who have a stooped posture but are also able to stand still. If they showed minimal body sway on the force platform, would it be possible to say they have good balance control?

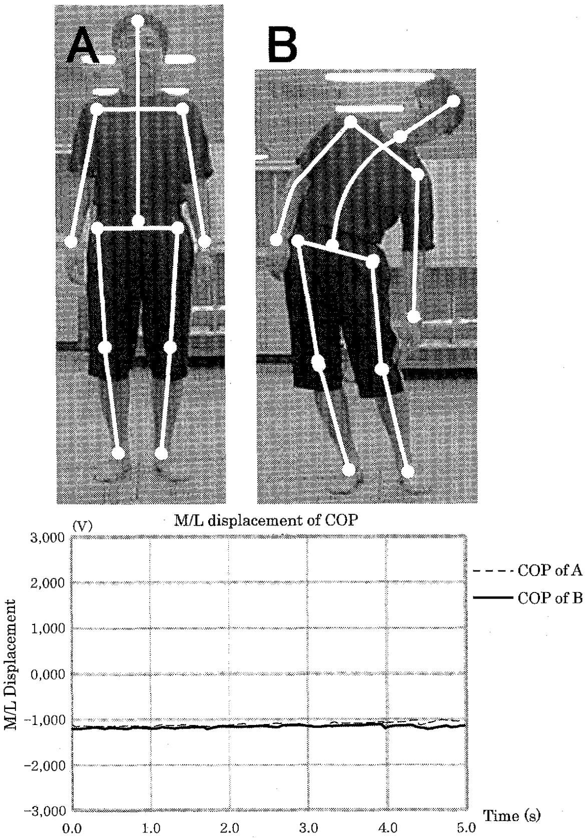

Fig. 1 Mediolateral (M/L) displacement of COP in quiet stance (A) and lateral bending stance (B). Note that M/L location of COP in A and B is almost same. Both of data indicate that the postural sway is minimal and stable

Definitions of the COM and COP

The COM is the point equivalent of the total body mass, or the point at which the weight of the body can be considered to act. Vertical projection of the COM onto the ground is often called the center of gravity (COG). Estimation of the COM of the multisegmented human body requires kinematic measurements of all body segment displacements and an anthropometric model of the body. Accurate estimation of small movements of the COM requires very precise measures of proximal and distal displacements of all individual body segments (Winter et al., 1998). Movements of the vertical projection of the COG of the body were previously calculated from photographic records of displacements of the mass centers of body segments (Murray et al., 1967). In recent years, 3–D motion analysis systems are used to calculate the COM. These systems can identify the position coordinates in 3–D by following the movement of markers attached to landmarks of the body with multiple cameras. Moreover, they can calculate the movement velocity, angle, angular velocity, and angular acceleration of the joints respectively. Using 3–D motion analysis systems, the 3–D trajectory of the whole body's COM can be computed from the weighted sum of the COM from each body segment. Meanwhile, actual COM data can never be calculated only by the force platform.

On the other hand, the COP is the point of the vertical ground reaction force vector. It represents a weighted average of all pressures over the surface of the area in contact with the ground (Winter, 1995). COP coordinates are derived from ground reaction forces registered with the aid of a force platform. It is possible to measure the magnitude of the vertical supportive force and also the movement of the action line of this force at its point of intersection with the supporting surface using the force platform. Although the vast majority of research on the quiet standing has used the COP from a single force platform as the outcome measure, there is a disadvantage whereby the force platform analysis measures the secondary consequences of swaying movements, not the movements themselves (Helen et al., 2001). When it is described in the literature that the path length of the COP and sway area are common measurement parameters in monitoring postural sway, many researchers view the excursions of the COP as body sway, which means the COM is swaying. Nevertheless, the fact is that the line of gravity and the center of pressure of the supportive force are two distinctly different phenomena, although they are closely related.

If one foot is on the ground, the COP lies within that foot. If both feet are in contact with the ground, the COP lies somewhere between the two feet, depending on the relative weight taken by each foot. Conversely, it is possible for the COM (COG) to be projected out of the base of support. The obtained data from the force platform, the linear length of the sway path (cm), the linear length of the sway path in a particular unit of time (cm/second), and the area of the sway path (cm^2), originate from the COP and not COM.

Quiet standing

1. Inverted pendulum model

It is considered that human bipedal standing is essentially unstable, and simply standing still normally requires continuous postural control. Trying to explain this control mechanism of the stationary bipedal stance, several authors have provided evidence that body sway in quiet standing is like the motion of an inverted pendulum pivoted at the ankle joint (Loram et al., 2002; Winter et al., 1998; Masani et al., 2006). Fig. 2 shows the inverted pendulum model to illustrate the body dynamics and kinematics during quiet stance. The body weight (W) is equal and opposite to the vertical reaction force (R), and these forces act at distances (g and p, respectively) from the ankle joint. At the moment of quiet stance shown in Fig. 2, the COM is located in front of the ankle joint. It is considered that the line of gravity usually passes ahead of the lateral malleolus in the sagittal plane. Consequently, the angular velocity (ω) is generated and the body will experience a clockwise, forward sway. In order to correct this forward sway, the COP must be anterior to the COG, as seen in Fig. 2. When the COP is more distant from the ankle joint than COM, the angular acceleration (α), which causes a counterclockwise,

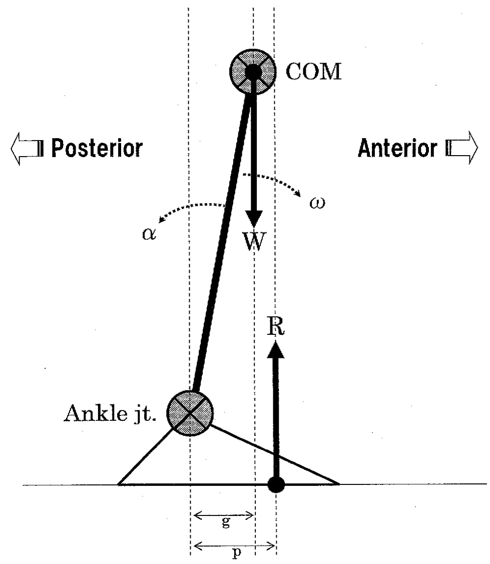

Fig. 2 Scheme of the inverted model in the sagittal plane. COM position is donated by variable (g). COP position is donated by variable (p). Angular acceleration (α) and angular velocities (ω) are shown by dotted arrows. W means body weight and R means vertical reaction force

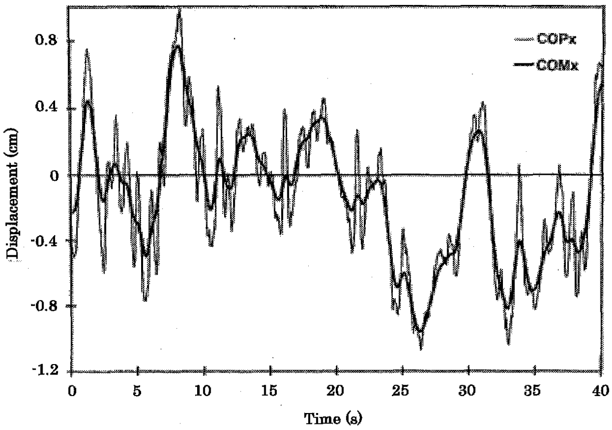

Fig. 3 Typical 40-s record from a subject standing quietly. COP and COM in anteroposterior direction show the COP to track the COM almost in phase. Reproduced from *J Neurophysiol.* 80: 1211–1221, 1998

posterior sway, will begin to act. When the COP is ahead of the COM the acceleration is reversed, and vice versa when the COP is behind the COM. It is shown in Fig. 3 that the dynamic range of the COP must be somewhat greater than that of the COG. This fact indicates that the COP is always moving with respect to the COG, increasing or decreasing the angular accelerations and velocities. It can be said that the COP is the controlling variable and COG is the controlled variable. Separation of the COP and COG, described as the CG-CP moment arm, is proportional to the COG horizontal acceleration in an ideal inverted pendulum model (Chang et al., 1999). The relationship between the COP and COG in the inverted pendulum model helps us to understand that the COP is continuously following the COM in order to keep the COM over the base of support. Although quiet standing looks stable, the COM and COP oscillate constantly. When we use the force platform, we should pay attention to the fact that fluctuations of the COM are smaller and smoother than those of the COP, which are obtained as raw data from the force platform in quiet standing.

2. Control of the COP in the anteroposterior direction

Fujiwara et al. (1984) suggested that the average of the COP position in quiet standing is located in the most stable anatomical structure of the foot, which is at the center of the longitudinal arch. This range corresponded to the area of the foot between Chopart's joint and the fifth metatarsal head, between about 30% and 60% of the foot's length. In this range, the tibialis anterior muscle was inactive, and the activity of the abductor hallucis muscle and the digitus pedis pressure were extremely small. Quiet standing can be maintained because the soleus, which is called one of the most important prime postural muscles, has the advantage of being able to respond to postural sway. As mentioned above, the COM is usually ahead of the ankle joint, so plantar flexing torque is continuously required to prevent the body from falling forward (Smith, 1957). Another study (Winter et al., 1998) argued according to the results of their experiments that in the A/P direction, subjects routinely stood with the COM ~5 cm anterior to the ankle joint. Thus, with the COP set to oscillate around 5 cm, the ankle plantarflexor moment for a 70-kg subject, for example, would be ~35 N·m. In generating this moment, the plantarflexors would have sufficient tone to generate a stiffness to cause the COP to move more than the COM when the pendulum sways. Increasing plantarflexor activity moves the COP anteriorly, while decreasing plantarflexor activity moves it posteriorly. When the central nervous system senses that anterior shift of the COG needs correcting, the COP increases by elevating plantarflexion activation until it lies anterior to the COG. In the A/P direction, the stabilization of balance during quiet standing is achieved largely by the stiffness of the ankle plantarflexors.

3. Control of the COP in the mediolateral direction

When we use two force platforms for the left and right feet, respectively, we can see independent left and right control at the ankle, and also observe a totally separate control of balance in the M/L direction. COP movement to the right would cause a lateral acceleration of the COM to the left. To cause the COP to move to the right, any one of the following muscle activations could be the cause: left ankle evertors, right ankle invertors, left hip adductors, and right hip abductors. Although it is easier to understand that the left hip adductors will move the body to the left, it might be confusing to image that the left ankle evertors will move the body to the left, since it is more natural to think that left ankle eversion will cause inclination of the body to the right. In the M/L direction, the ankle and hip muscles activate in coordination as a parallelogram defined by the two ankles and two hip joints. Because of the small width of the foot, the maximum moment that could be generated by either invertors or evertors would be about 10 N·m. The hip abductors/adductors could generate in excess of 100 N·m in emergencies. When the ankle and hip muscles contract simultaneously, the hip muscles dominate the ankle muscles. The hip muscles are agonists to move the body laterally and the ankle muscles are fixators to transmit the power of the hip muscles. Winter (1995) stated that the dominant control in the M/L direction is due to the load/unloading mechanism by hip muscles and not due to ankle muscle control of the left and right. As a result of such joint movements, the weights of the pelvic girdle, trunk, and head are greater on one side, the left or right lower extremity.

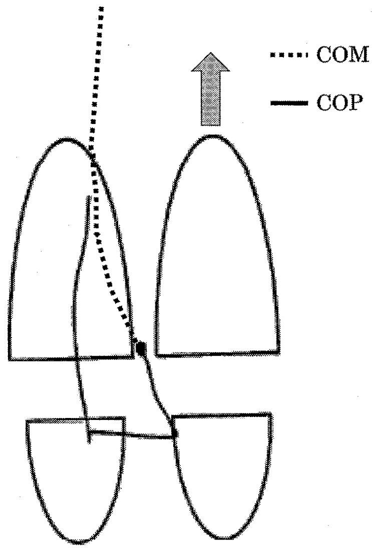

Fig. 4 COM and COP trajectories during gait initiation of a representative healthy young person. The right is the swing limb and the left is the stance limb. COM and COP moves dissimilar direction. Reproduced from *Journal of Neurological Physical Therapy* 28: 2–11, 2004

Gait initiation

The task in standing is to keep the body's COM safely within the base of support. However, the task in walking is quite different from the quiet stance. When we wish to start walking, we must put our balance into disorder, controlling the COP to move the COM, which would be almost always outside the base of support during walking. In quiet standing, the COM and COP are related, which might be one of the reasons for confusing them. In contrast, the difference between the COM and COP is emphasized in gait initiation because they move respectively, not in phase.

The following is an explanation of gait initiation by Winter (1995). Prior to initiation, the gastrocnemii and soleus are active to hold the COM in some equilibrium position anterior to the ankle joint. At initiation, these muscles are relaxed to allow the inverted pendulum to accelerate forward, followed by a drastic increase in the tibialis anterior activity to pull the inverted pendulum forward. Then, when the body has sufficient forward lean and velocity, the stance limb plantarflexors became active again, to achieve a forceful push-off. During the very initial phase of initiation, the COP is seen to move posteriorly as the COM accelerated forward. In the M/L direction the COP was seen to shift initially towards the swing limb, then rapidly across to the stance limb. The posterior movement of the COP results from a momentary decrease in plantarflexor activity (aided partially by an increase in dorseflexor activity). The lateral movement of the COP towards the swing limb is due to an increased loading of that limb by its hip abductors.

As shown in Fig. 4, gait initiation begins with the movement of the COP posterolaterally toward the extremity that will become the initial swing extremity, whereas the COM moves anterolaterally toward the initial stance extremity for loading the body weight on it. The characteristic separation of the COM and COP is an important feature of gait initiation. Several studies have examined the characteristics of gait initiation in young and elderly individuals with no known neurologic problems or individuals with impaired postural control (Burleigh et al., 1994; Chang et al., 1999; Matthew et al., 2002). They have reported that the COM-COP distance in younger subjects was significantly greater than in elderly subjects or subjects with Parkinson's disease. These findings pointed out that the peak COG-COP moment arm during gait initiation indicates the subject's tolerance of dynamic unsteadiness. During activities, the person is required to move the COM away from the stable starting position, where COM and COP projections are aligned, producing an inherently unstable posture, where COM and COP projections are separated. The greater the COM-COP distance, the more active postural control is needed. Shortening of the COM-COP distance may reflect a need to preserve stability because of impairments of postural control mechanisms like in individuals with Parkinson's disease.

Thus, the separation of the COM and COP in gait initiation can be used to evaluate the ability of balance control in dynamic activities. Research on the relationship between the COM and COP in gait initiation has shown us that the COM and COP are totally different.

Conclusion

We have discussed the control of balance, focusing on the relationship between the COM and COP. We used the inverted pendulum model to explain the biomechanical mechanism of balance control in quiet standing and gait initiation. In fact, human movement is more complex than an inverted pendulum since there are multiple segments comprising the human body. The task of balancing a real inverted pendulum in one plane is much simpler to investigate because there are fewer variables.

As mentioned at the beginning, the purpose of this paper was to elucidate the differences between the COM and COP, for they have been misused when referring to body sway. To collect and analyze data on the COM and COP is one of the techniques used to quantify postural control, called posturography (Horak, 1997). Since quantitative posturography is both cost- and time-intensive, clinical therapists involved in rehabilitation commonly use the more easier functional balance tests to evaluate the performance in motor tasks, such as the Performance-Oriented Assessment of Mobility (Tinnetti, 1986), Berg Functional Balance Scale (Berg et al., 1995), or Functional Reach Test (Duncan et al., 1990). Although these tests were proven to reflect the subjects' ability to balance, sometimes it may be too difficult to maintain stability and orientation during such tests for patients with impaired stability. Regardless of the patients postures are able to take, during quiet standing or dynamic activities, clinical therapists are required to observe and analyze their movements to properly grasp their balance abilities. Even if no systems for posturography are available, it would be helpful for clinicians to evaluate patients' abilities to balance by understanding the relationship between the COM and COP.

Few studies have reported how the relationship between the COM and COP would change during various activities, and what the causes of the shortening of the COM-COP distance are. These questions should be answered by future studies. We consider such investigations valuable in order to prevent falls.

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