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An Experimental Analysis of Stability in Human Walking

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Abstract

Biped locomotion has excellent environment adaptability due to natural selection and evolution over hundreds of millions years. However, the biped walking stability mechanism is still not clear. In this paper, an experimental analysis of walking stability in human walking is carried out by using a motion capture system. A new stability analysis method is proposed based on Zero Moment Point (ZMP) and Sliding Time Window (STW). The influences of ground friction coefficient, ground slope angle and contact area of support polygon on human walking stability are investigated. The experiment is carried out with 12 healthy subjects, and 53 passive reflective markers are pasted to each subject to obtain moving trajectory and to calculate lower limb joint variation during walking. Experimental results show that ground friction coefficient, ground slope angle and contact area have significant effects on the stride length, step height, gait cycle and lower limb joint angles. When walking with small stability margin, subjects modulate gait to improve the stability, such as shortening stride length, reducing step height, and increasing the gait cycle. These results provide insights into the stability mechanism of human walking, which is beneficial for locomotion control of biped robots.

Keywords: human locomotion, walking stablity, walking gait, biped robot, motion caption system

1 Introduction

Biped robot is attracting flourishing research interests because of its exceptional ground adaptability[1,2]. Researchers have proposed many bipedal gait patterns based on Zero Moment Point (ZMP) to achieve stable locomotion, such as ASIMO[3], ATLAS[4], HRP-2[5] and QRIO[6]. However, the robot gait of such a walking pattern lacks naturalness and has low energy-efficiency[7].

Human locomotion analysis includes kinematics analysis, dynamic analysis and dynamic electromyography (EMG) signals analysis, which provides a great deal of inspiration for biped robot[8]. Qian *et al.* revealed the mechanism of the impact attenuation and energy absorption functions of the human foot complex[9]. Zhao *et al.* investigated the delicate *in-vivo* kinematic coupling between different functional regions of the human spinal column during locomotion[10]. Gao *et al.* reported that the EMG amplitudes are different when human walking on icy surface and treadmill surface[11]. Kwon *et al.* investigated the changes in hip, knee and ankle kinematic variables of the lower extremities at different gait speeds by using a VICON 3D motion analysis system and force plates[12].

Gait stability is very important for human locomotion. Bruijn *et al.* investigated the effects of arm swing on human gait stability[13]. Kang *et al.* studied the effects of walking speed, strength and range of motion on gait stability in healthy older adults[14]. Hak *et al.* studied the effect of balance perturbations on walking speed, step length, step frequency, and step width was measured[15]. Debbi *et al.* proposed that almost all kinematic and dynamic gait parameters are sensitive to changes in global instability, and the most sensitive are parameters measured at the knee[16].

ZMP is widely used as a gait stability criterion for biped robot. It is defined as the point on the ground about which the sum of all the moments of the active forces is equal to zero[17]. To guarantee the stability of the biped robot, the ZMP must be within the support polygon formed between the foot and the ground[3]. Researchers have combined ZMP with classical and modern linear controllers to realize different locomotion functionalities[18–20]. Caron *et al.* proposed a method for multi-contact mobility under frictional constraints based on

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ZMP[21]. Luat *et al.* proposed the fuzzy controller based on ZMP to maintain the balance of walking[22]. However, the ZMP often distributes outside the support polygon during the process of human walking. This indicates that the ZMP provides a necessary (nonsufficient) condition for walking stability.

The target of this paper is to study the mechanism of human walking stability. An improved stability evaluation method is proposed based on ZMP and Sliding Time Window (STW), which uses the historical ZMP data to evaluate the current stability of walking. Compared with the traditional ZMP criterion, the new stability assessing method takes account into the case of ZMP outside the support polygon. This extends the distribution range of ZMP and is more suitable for human dynamic walking. Vicon Nexus, which is a commercial motion capture system, is used to analyze the operation of human walking in different environment. The influences of ground friction coefficient, ground slope angle and contact area of support polygon on human walking gait are investigated. Furthermore, the relationship between gait adjustment and walking stability in different environments is also studied. The results can be used as reference for the walking control of biped robots.

2 An improved stability criterion based on ZMP and STW

The ZMP in the *X*-*Z* plane can be calculated as[7]:

$$\begin{cases} X_{\mathrm{ZMP}} = \dfrac{\sum_{i=0}^{n} m_i (\ddot{y}_i + g) x_i - \sum_{i=0}^{n} m_i \ddot{x}_i y_i}{\sum_{i=0}^{n} m_i (\ddot{y}_i + g)} \\ Z_{\mathrm{ZMP}} = \dfrac{\sum_{i=0}^{n} m_i (\ddot{y}_i + g) z_i - \sum_{i=0}^{n} m_i \ddot{z}_i y_i}{\sum_{i=0}^{n} m_i (\ddot{y}_i + g)} \end{cases}, \tag{1}$$

where X_{ZMP} and Z_{ZMP} are coordinates in X and Z axises, respectively. n is the number of body segments. x_i and $\ddot{x}_i$ are the displacement and acceleration of the ith segment in X axis, respectively. y_i and $\ddot{y}_i$ are the displacement and acceleration of the ith segment in Y axis, respectively. z_i and $\ddot{z}_i$ are the displacement and acceleration of the ith segment in Z axis, respectively. g is the gravity.

The ZMP location can be normalized as:

$$SM1 = d_1 / d_2, \tag{2}$$

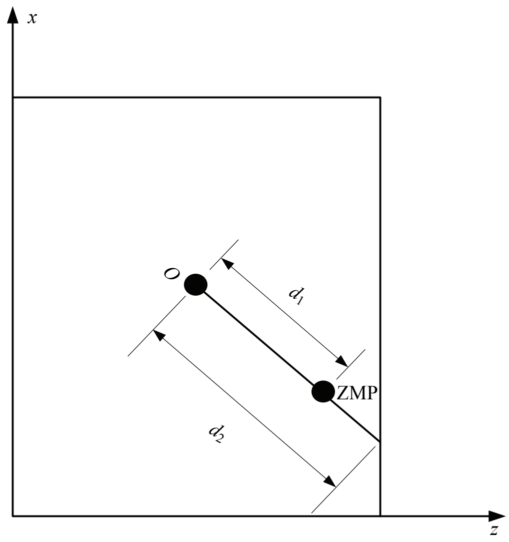

Fig. 1 Schematic diagram of ZMP normalization.

where $SM1$ is the normalized ZMP, d_1 is the distance between ZMP and the Center Point (CP) of the support polygonal, d_2 is the distance between the CP and the intersection point of CP-ZMP extending line and support polygonal boundary, as show in Fig. 1.

Thus, the stability criterion can be represented as:

$$SM1 < 1, \text{stable}; SM1 \geq 1, \text{unstable}. \tag{3}$$

When $SM1 < 1$, the ZMP is within the support polygon, which means walking is in stable state. When $SM1 \geq 1$, the ZMP is outside the support polygon, which is in an unstable state. Due to sensitive perception and feedback ability, human can restore stability by adjusting posture in the later case. It indicates that the ZMP criterion has limitation in the stability analysis of human walking.

The sliding window is a flow control technique and widely used in data stream classification. From the perspective of statistics, the time series are substantially the sequence arranged chronologically valued at different time. There is a trend of the correlation between the past value and future value in time series[23]. The schematic diagram of STW is shown in Fig. 2. The historical data streams during different time have different effect on current data streams. The correlation depends on the time interval between historical data stream and current data stream. The smaller the time interval is, the stronger correlation between the historical data stream and current data stream is. Hence, for each time window, the

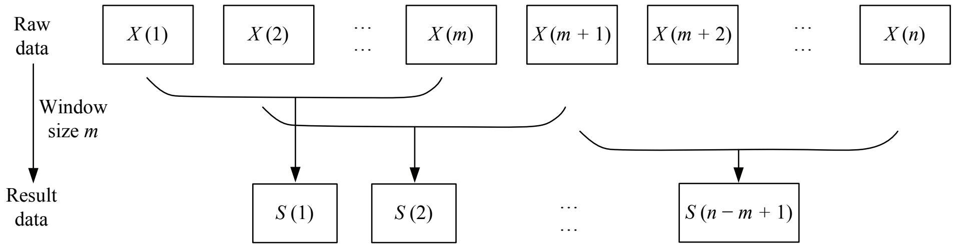

Fig. 2 The algorithm of STW.

window weight associated with the time series is introduced. The weight value can be selected based on the effects of current attribute.

Human locomotion is a periodical motion. According to the STW principle, the historical stability data has effect on the current state. If ZMP is outside the support polygon, walking stability can be restored through gait adjustment in the situation of walking stable in the past few periods. However, human may fall down when ZMP is outside the support polygon in the case of walking in critical stability for a period in the past. In light of the effects of historical state, we improve the stability criterion with ZMP combining the idea of STW, which can be written as:

$$SM2 = \sum_{i=1}^{m} \alpha_i SM1_i, \quad \left(\sum_{i=1}^{m} \alpha_i = 1\right), \tag{4}$$

where $SM2$ is the improved ZMP, m is the window size, $SM1_i$ and α_i are the ith normalized ZMP and the weight of historical stability to current gait stability, respectively. Note that the historical stabilities at different time have different degrees of influence on current state. The closer to the current time, the greater the effect and the value of α_i is. In addition, the coordinates of ZMP, d_1 and d_2 can be calculated based on motion capture system and simplified human model.

Thus, the improved stability criterion can be represented as:

$$SM2 < \delta, \text{stable}; SM2 \geq \delta, \text{unstable}, \tag{5}$$

where δ is the threshold value of $SM2$, which can be obtained by human walking experiment.

The improved stability evaluation method can be used for realizing dynamic walking for biped robot. For example, the new stability evaluation method can be used instead of traditional ZMP for modulating the activity of Central Pattern Generator (CPG) in our previous work about biped robot control[7]. The CPG is designed to generate the desired motion for each joint of the robot. More details about the kinematic/dynamic models and gait trajectory generator of biped robot please see Ref. [7]. In this situation, the threshold value δ and window size m can be obtained by optimization method.

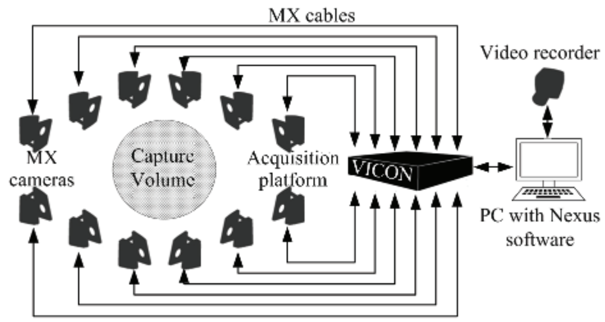

Fig. 3 The scheme of Vicon Nexus motion capture system.

3 The experiment and analysis of gait

The effects of the ground friction coefficient, ground slope angle and the contact area of support polygon on human walking stability are studied by experiment. The experiment is carried out by using Vicon Nexus motion capture system. The scheme of this system is shown in Fig. 3, which is consisted of 12 MX cameras with capture rate 120 frame·s^{-1}, acquisition platform unit, MX cables, a host PC with VICON software, and a video recorder. Total 53 markers were placed on each subject according to VICON standard template[24].

With the above mentioned experimental setup, three experiments of walking with different ground friction coefficient, ground slope angle and contact area of support polygon were carried out, as shown in Fig. 4. Date for this study was obtained from 12 healthy adults (6 males and 6 females). For each person, each type of

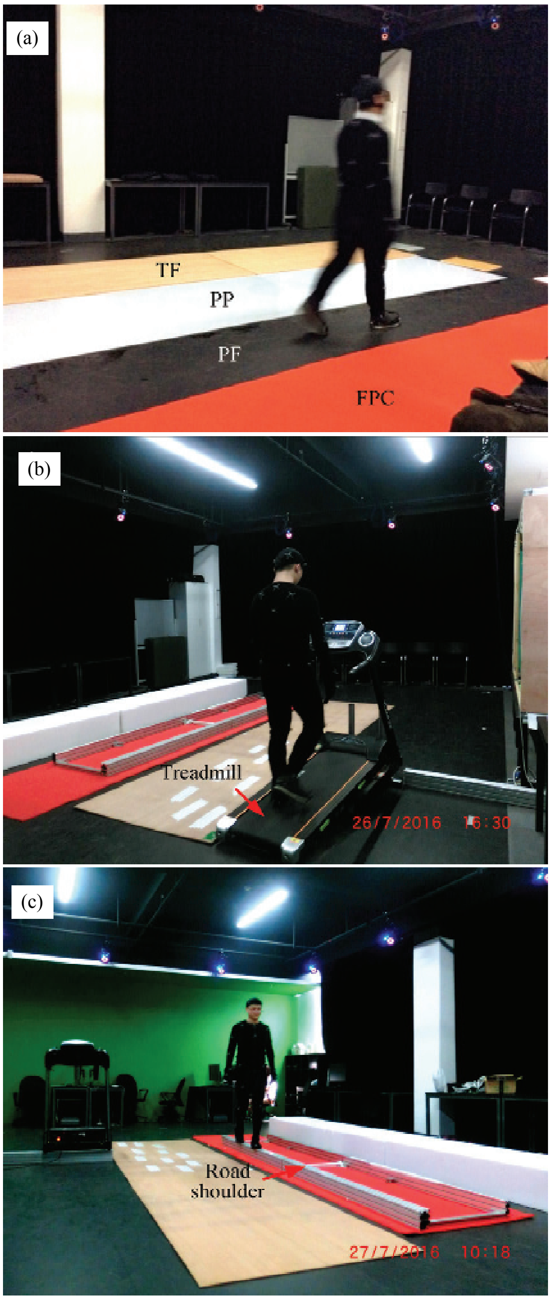

Fig. 4 The experiments of (a) ground friction coefficient, (b) ground slope angle, and (c) contact area. Fiber Plastic Carpet (FPC), Plastic Floor (PF), Timber Floor (TF) and white Polypropylene Panel (PP).

experiment was carried out for three times. All subjects wore the same shoes. Since human locomotion in the coronal and transverse plane is not obvious, in this paper we only considered those in the sagittal plane. MATLAB was employed to calculate gait parameters and data analysis. In order to compare the changes of variability for step parameters, we averaged the variability for each of these experiments over all subjects.

3.1 The gait experiment

3.1.1 Human walking with different ground friction coefficients

Each subject was asked to walk on four kinds of materials at random order: Fiber Plastic Carpet (FPC), Plastic Floor (PF), Timber Floor (TF) and white Polypropylene Panel (PP) sprayed with water, where the friction coefficients are 0.602, 0.502, 0.480 and 0.345, respectively. It should be noted that after each subject walk on the PP floor, the water should be sprinkled immediately. The experimental order of each subject is recorded then.

3.1.2 Human walking with different ground slope angles

Each subject was required to walk on treadmill with different slope angle at random order. The slope angles are 10˚, 20˚ and 30˚, respectively, and the speed of treadmill is set to 1.2 m·s^{-1}. The experimental order of each subject is recorded then.

3.1.3 Human walking with different contact areas of support polygon

Each subject was required to walk on two different width road shoulder (8 cm and 4 cm, respectively) in random order with the most comfortable pace. The experimental order of each subject is recorded then.

3.2 The experiment analysis

Due to the differences in physique of each subject, it has a certain effect on the generality of results. In order to avoid the influencing of foot length on stride length, a dimensionless stride length can be given as:

$$s_1 = \frac{\textit{Stride length}}{\textit{Foot length}}, \tag{6}$$

where s_1 is the dimensionless stride length.

3.2.1 The effect of ground friction coefficient on human walking

(1) The effect of ground friction coefficient on gait parameter

The average gait parameters of 12 subjects walking on the ground with four different friction coefficients are shown in Fig. 5. This indicates that with the reduction of friction, the stride length gets shorter. The stride length with PF is 7.6 % less than that with FPC, as shown in

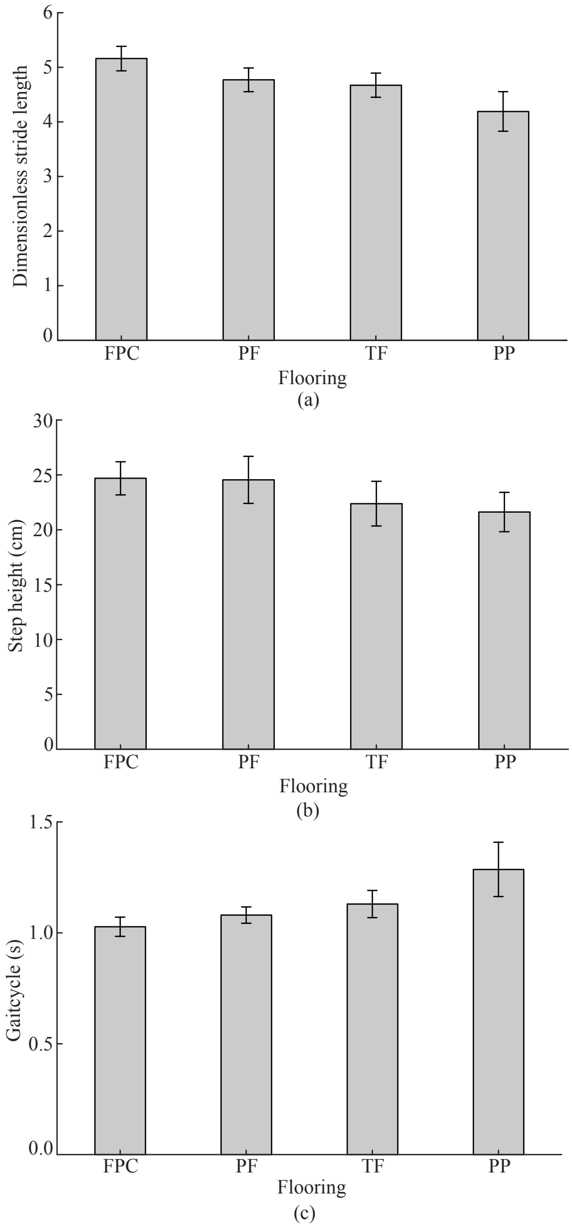

Fig. 5 The effects of ground friction coefficient on (a) stride length, (b) step height, and (c) gait cycle.

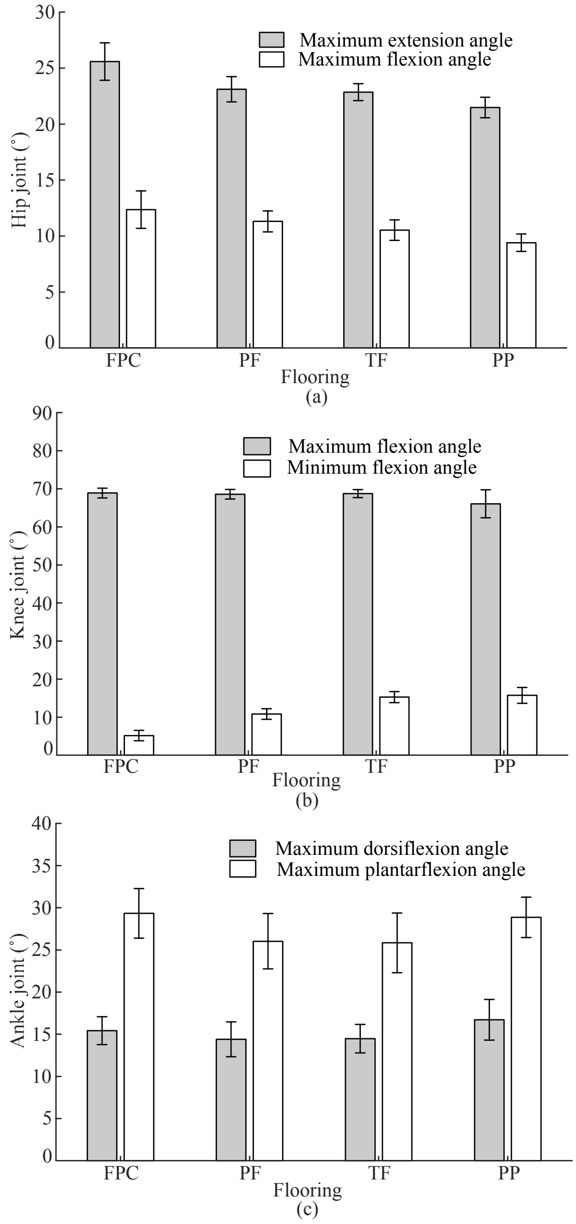

Fig. 6 The effects of ground friction coefficient on (a) hip joint, (b) knee joint, and (c) ankle joint.

Fig. 5a. With the decrease of friction, the step height gets lower, as shown in Fig. 5b. Though there is little variation when walking on the grounds of FPC and PF, the step height is lower by 9.3% when the subjects walk on ground of TF compared with FPC. This manifests that human needs to modulate gait parameters to keep stable. It is consistent with the research of Chen *et al.*[25]. Fig. 5c shows that the gait cycle increases with the reduction of friction. It reveals that the gait cycle is increased by 13.8% when walking on ground of PP compared with TF. This indicates that as the friction coefficient decreases, human needs to spend more time to maintain walking stable.

The experimental results show that gait parameters have minor changes when walking on the grounds of FPC, PF and TF, but differ dramatically when walking on the ground of PP. This is because the ground with large friction can provide enough driving force (friction force) to keep stable walking. However, as the ground friction decreases, human needs to change gait parameters to keep stable walking. Moreover, the slippery ground may lead to gait disorder. It makes human can not adjust gait timely and causes falling down.

(2) The effect of ground friction coefficient on lower limb joint motion

Due to human walking with symmetry, only the right limb is analyzed for the movement of lower limb joints. The average hip joint angles of all subjects walking on ground with four different friction coefficients are shown in Fig. 6a. The maximum extension angle and maximum flexion angle of hip joint reduce with the decrease of friction coefficient. This is because the more slippery the ground is, the smaller the joint motion range is, which making the stride length shorter and the Center of Mass (COM) lower.

The average knee joint angles of all subjects walking on ground with four different friction coefficients are shown in Fig. 6b. The result suggests that the maximum flexion angles are almost the same when the subjects walk on the ground of FPC, PF and TF. However, the results show that the friction coefficient affects significantly the minimum flexion angle and knee joint range of motion. It is found that with the decrease of friction coefficient, the motion range of knee joint reduces. As the ground material changes from FPC to PF and from TF to PP, the corresponding motion ranges of knee joint reduce by 1.5 % and 4.8 %, respectively. The minimum flexion angles are similar when walking on ground of TF and PP. This implies that in the case of the friction coefficient of 0.480, the flexion angle that guarantees stable walking is large enough even if the friction reduces.

The average ankle joint angles of all subjects walking on ground with four different friction coefficients are shown in Fig. 6c. It can be seen from the figure that the maximum dorsiflexion angles of ankle joint with the ground of FPC, PF and TF are relatively similar. However, the maximum dorsiflexion angle on the ground of PP is greater than other three kinds of ground. In addition, when the friction coefficient is greater than 0.480, the minimum plantarflexion angle reduces with the decrease of friction coefficient, and then the angle increases in the case of the friction coefficient is less than 0.480. This is because the slippery of foot in the process of walking on the PP flooring.

Through the experiment, it is verified that the friction coefficient has a significant effect on walking stability. The results show that with the decrease of the ground friction, the stride length shortens, step height lowers, the hip joint and knee joint motion ranges reduces, while the gait cycle increases. Moreover, the ankle joint range of motion reduces firstly and then increases as the friction coefficient decreases to a certain extent.

3.2.2 The effect of ground slope angle on human walking

(1) The effect of ground slope angle on gait parameter

The average gait parameters of 12 subjects walking on different ground slope angles are shown in Fig. 7. Fig. 7a shows that the stride length reduces with the rise of slope angle. The result shows that when the slope angle reaches 30˚, the variability of stride length is the biggest. This indicates that the walking stability is disturbed significantly by the large ground slope angle. Fig. 7b shows that the height of swing foot reduces as the slope angle increases. The reason is that the ground reaction force reduces with the increase of slope angle, which leads to the decrease of the static friction force. Therefore, in order to avoid falling down due to uneven force, the height of swing foot reduces. Fig. 7c shows that the gait cycle improves with the slope angle increase. This indicates that human needs more time to maintain stable walking on slope ground. When the slope angle increases from 10˚ to 20˚, the gait cycle increased by 11.4%. However, as the slope angle increases from 20˚ to 30˚, the gait cycle increased by 1.4%. This means that human stability cannot be obtained by simply increasing the gait cycle.

(2) The effect of slope angle on lower limb joint motion

The average hip joint angles of all subjects walking on the ground with three different slope angles are shown in Fig. 8a. The figure indicates that with the slope angle increases, the maximum extension angle and maximum flexion angle both increase. This is because human adjusts hip joint movement to maintain stable walking in the case of large slope angle.

The average knee joint angles of all subjects walking on the ground with three different slope angles are shown in Fig. 8b. It is observed that there are

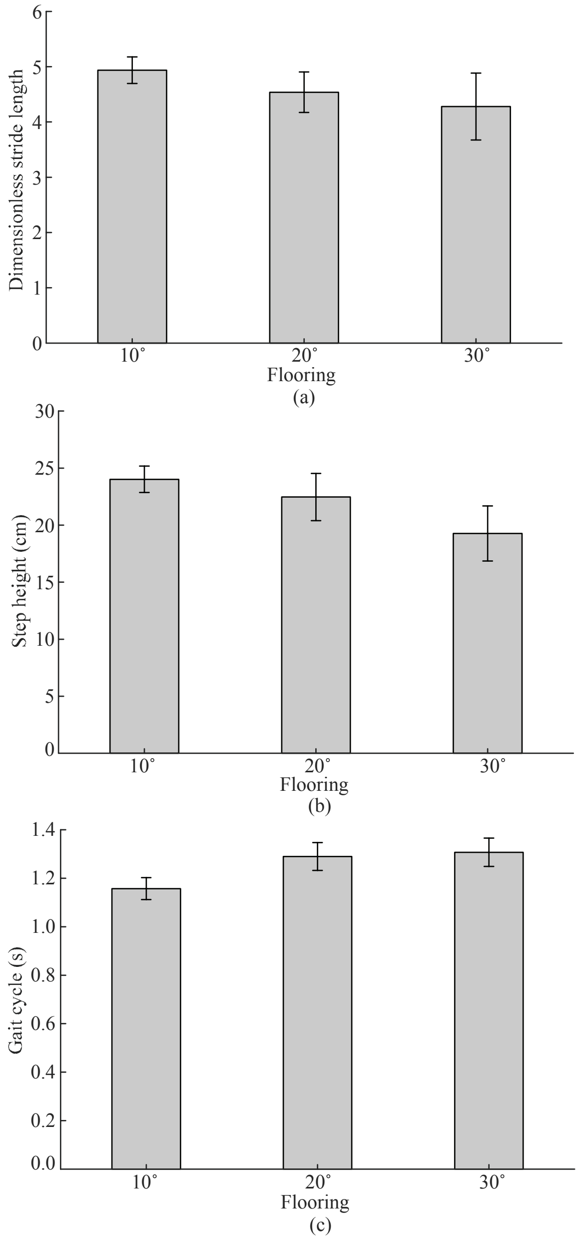

Fig. 7 The effects of ground slope angle on (a) stride length, (b) step height, and (c) gait cycle.

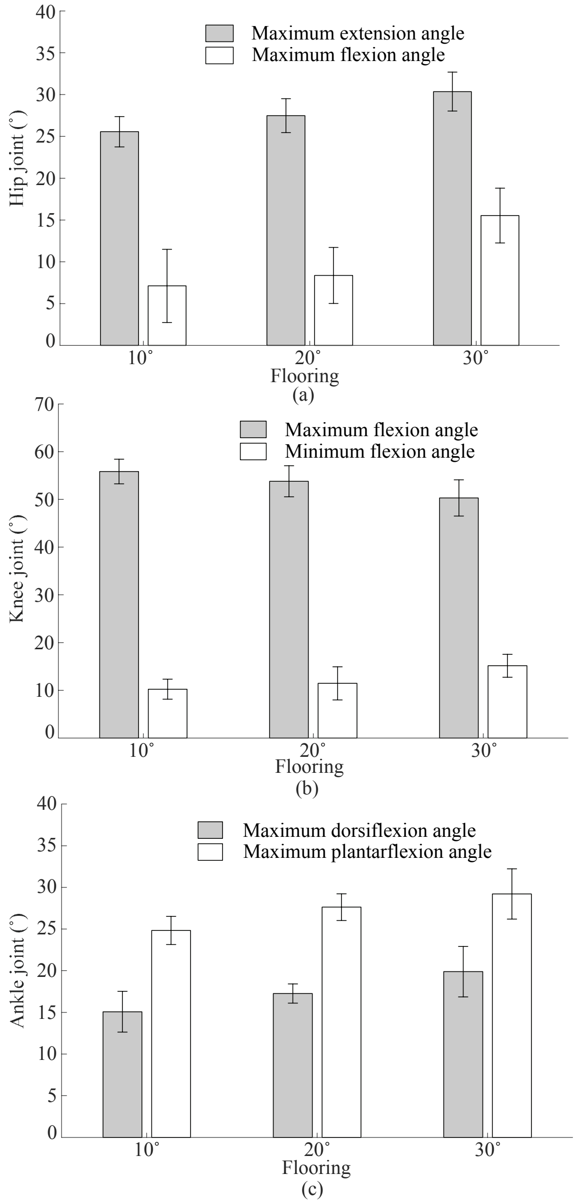

Fig. 8 The effects of ground slope angle on (a) hip joint, (b) knee joint, and (c) ankle joint.

significant effects of slope angle on both the maximum flexion angle and minimum flexion angle. With the increase of slope angle, the maximum flexion angle reduces and the minimum flexion angle increases, indicating the reduction of joint motion range.

The average ankle joint angles of all subjects walking on the ground with three different slope angles are shown in Fig. 8c. The maximum dorsiflexion angle and the maximum plantarflexion angle of ankle joint both increase with the rise of slope angle. This is because human needs to land more gently when walking on the ground with large slope angle.

To sum up, along with the slope angle increases, the stride length shortens, step height lowers and the motion range of knee joints reduces, while the gait cycle, the hip joint and ankle joint motion ranges both increase. Kim *et al.* concluded that in case of human walking on the ground with some slope, the torso angle erects and the pelvis center shifts a little forward to resist fall back[26]. It is the reason that the joint angles in lower limb vary with the increase of slope angle.

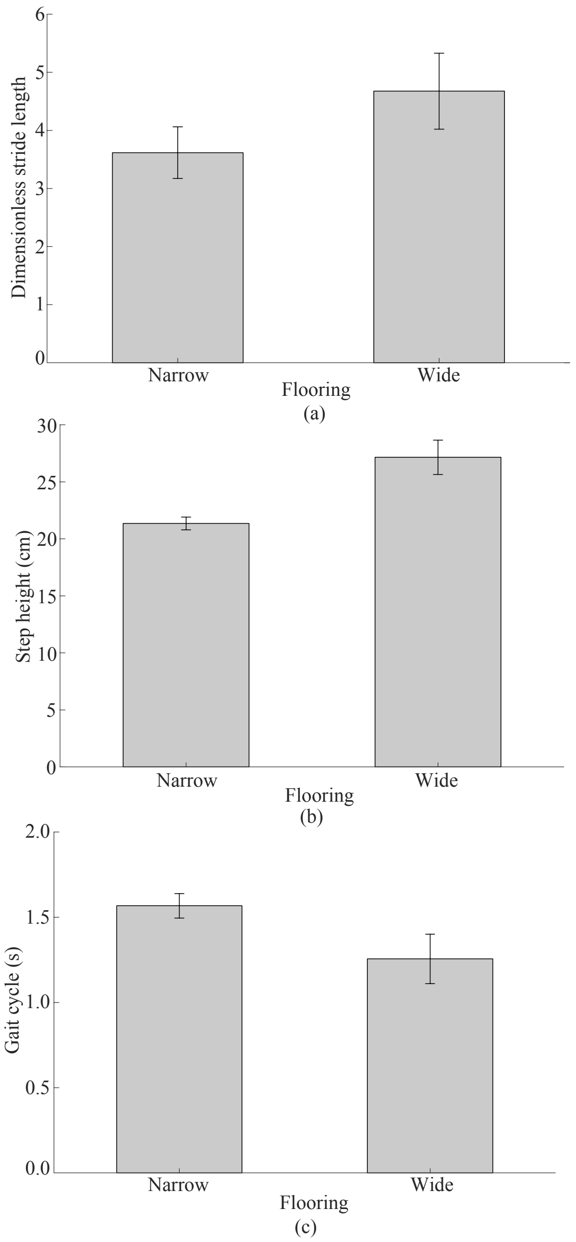

Fig. 9 The effects of contact area on (a) stride length, (b) step height, and (c) gait cycle.

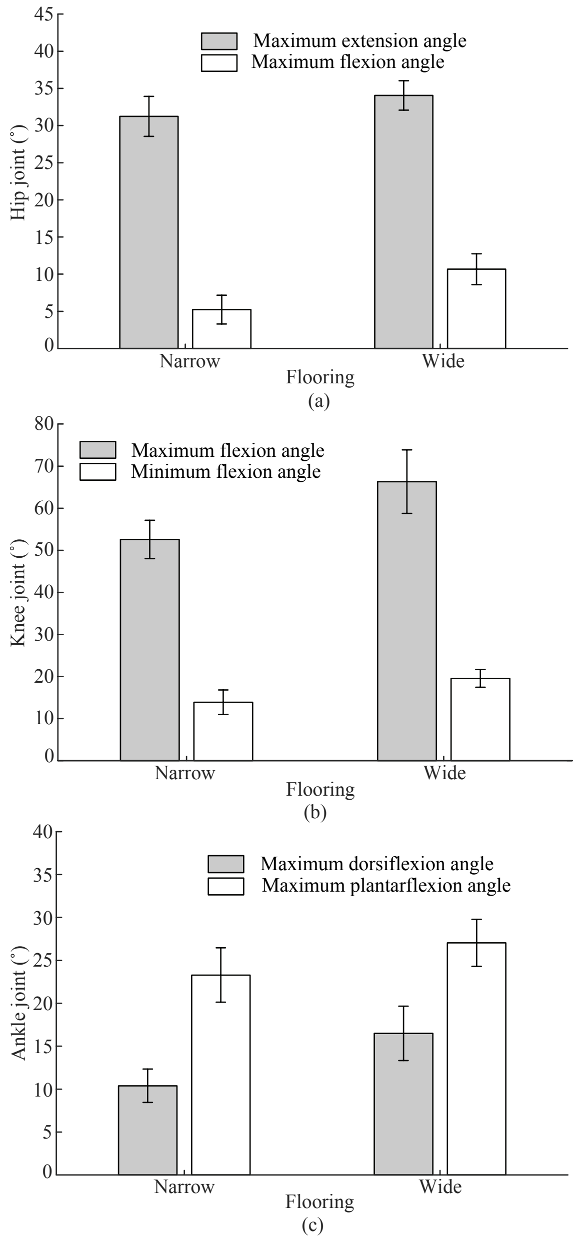

Fig. 10 The effects of contact area on (a) hip joint, (b) knee joint, and (c) ankle joint.

3.2.3 The effect of contact area of support polygon on human walking

(1) The effect of contact area of support polygon on gait parameter

The gait parameters of 12 subjects walking on the road shoulder with different widths are shown in Fig. 9. It can be seen that the ground width has a significant effect on both the stride length, step height and gait cycle. When the subjects walking on the narrow road shoulder (4 cm width), the stride length is shorter than that walking on the wide one (8 cm width), as shown in Fig. 9a. The step height improves with the increase of contact area, as shown in Fig. 9b. In addition, the gait cycle increases when walking on the narrow road shoulder, as shown in Fig. 9c. The results show that the reduction of contact area decreases the stability margin of human walking, leading to the increase of unstable possibility.

(2) The effect of contact area of support polygon on lower limb joint motion

The average hip joint angles of all subjects walking on ground with two different widths are shown in Fig. 10a. The figure shows that maximum extension angle and maximum flexion angle of hip joint both increase with the contact area. This is owing to the decrease of ground width that reduces the size of stability area and walking stability, making the maximum extension and flexion angles of hip joint reduce. It is found that during the experiment, many subjects stretch arms to increase stability in the coronal plane.

The average knee joint angles of all subjects walking on ground with two different widths are shown in Fig. 10b. The figure indicates that with the improvement of the contact area, the maximum flexion angle and minimum flexion angle both increase. In addition, the motion range of knee joint with narrow ground is smaller than that one with wide ground. This means that human usually reduce motion range of knee joint to make up the reducing of stability margin.

The average ankle joint angles of all subjects walking on ground with two different widths are shown in Fig. 10c. It can be seen that when the subjects walk on the narrower ground, the corresponding maximum dorsiflexion angle and maximum plantarflexion angle are smaller. This is due to the subjects handling the instable factor in coronal plane with more cautions.

The experimental results show that with the contact area improves, the stride length, step height and the motion range of lower limb joints increase, while the gait cycle decreases. In conclusion, we can find that the changes in external environment affect the walking posture. In order to improve stability, the subjects adjust walking posture, making up for environmental interference. The stability mechanism of human walking in different environments can provide reference for biped robot control.

4 The stability analysis

4.1 The effect of ground friction coefficient on stability

The values of *SM*1 and *SM*2 mentioned in section **2** can be considered as the stability margins for human walking analysis. The lower the *SM*1 and *SM*2 are, the more stable the human walking is. Thus, the average

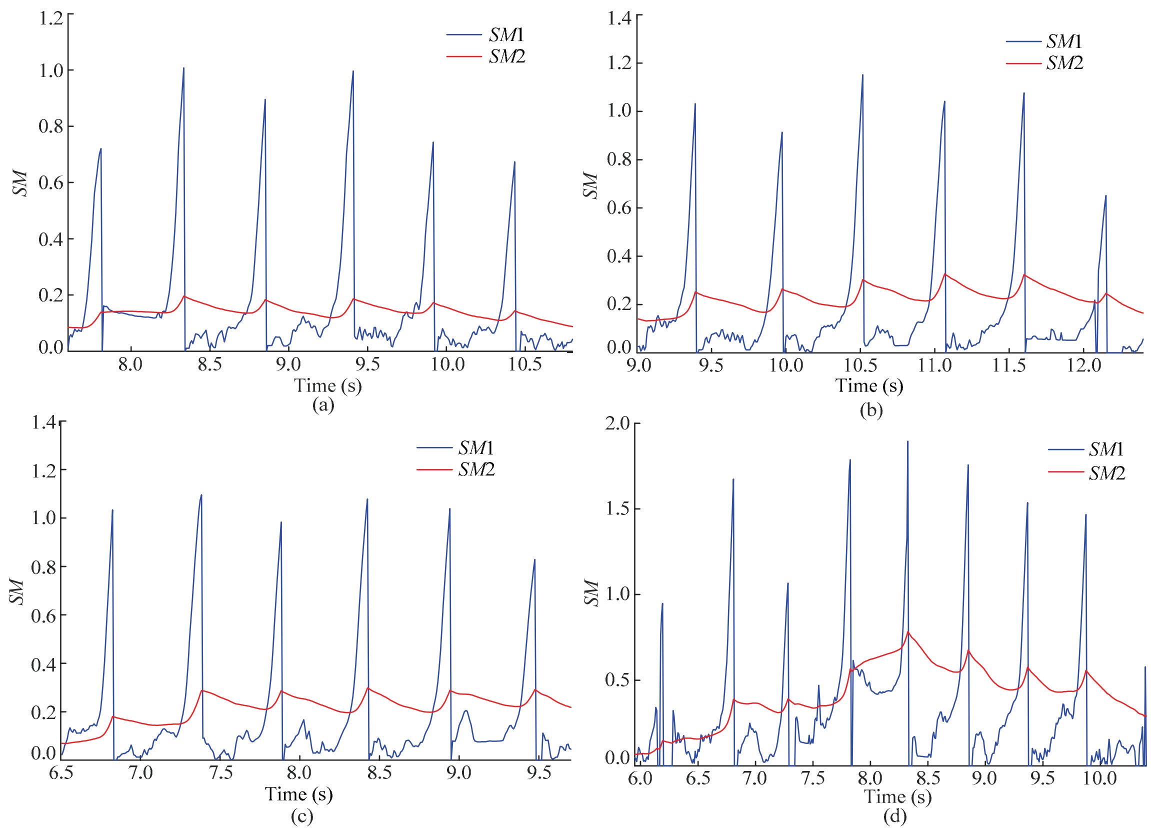

Fig. 11 The effects of friction coefficient on the walking stability. (a) FPC, (b) PF, (c) TF, (d) PP.

trajectories of stability margins as human walk on the ground with four different friction coefficients are shown in Fig. 11. The results show that the values and trends of *SM*2 are similar when the subjects walk on the ground of FPC, PF and TF, as shown in Figs. 11a–11c. The results indicate that the friction of the three kinds of ground is rough enough to maintain human stable walking. Fig. 11d shows that when walking on PP (the friction coefficient is 0.345), the fluctuations in walking process have been shown and the value of *SM*2 is greater compared with Figs. 11a–11c. This suggestions that when the friction coefficient is smaller than 0.480 (the friction coefficient of TF), the difficulty of walking stability recovery is increased. In addition, the results show that ZMP is sometimes outside the support polygon ($SM1 > 1$), especially in Fig. 11d, indicating the falling down of human. However, all subjects accomplished the experiment safely. This verifies that the traditional ZMP method is only a necessary condition for walking stability, and the improved stability evaluation method is more reasonable for biped walking analysis.

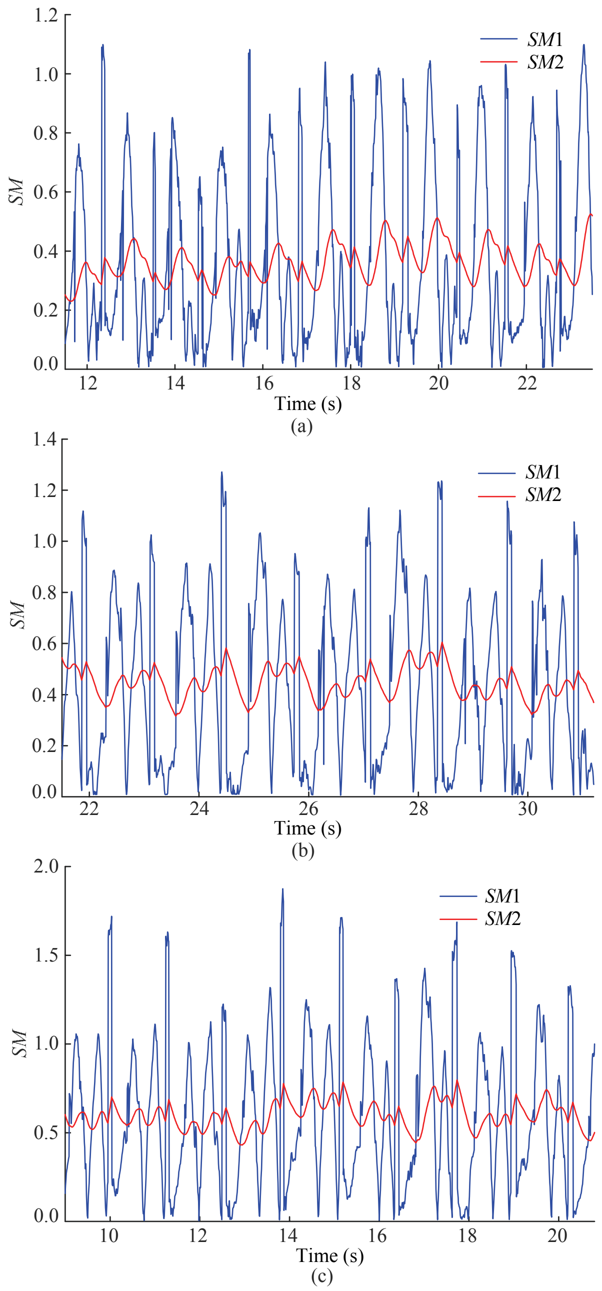

Fig. 12 The effects of slope angle on the walking stability. (a) 10°, (b) 20°, (c) 30°.

4.2 The effect of ground slope angle on stability

In the case of ground slope angle increases, the subjects maintain stable walking by shortening stride length, extending gait cycle, increasing motion ranges of the hip joint and ankle joint, and reducing the motion range of knee joint. Although the subjects cope with the adverse factors through the gait adjustment, there are

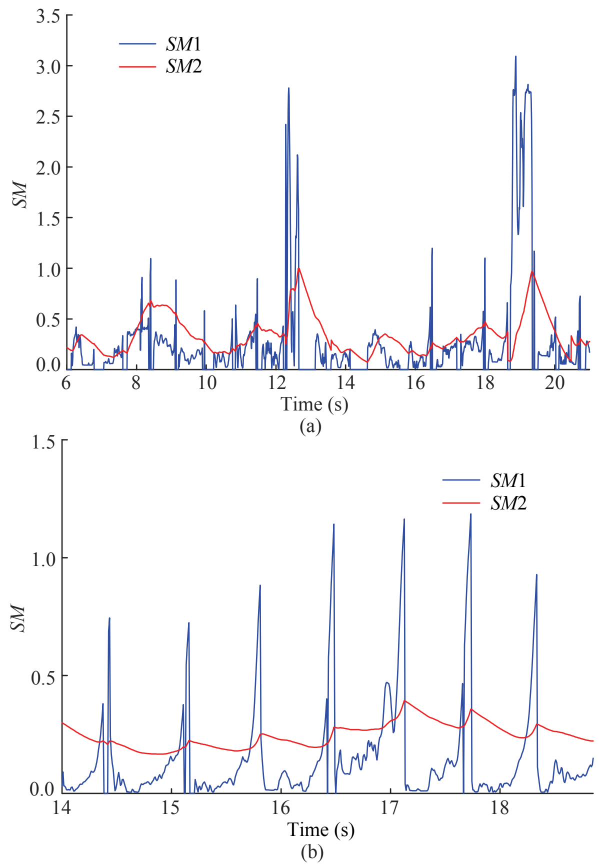

Fig. 13 The effects of contact area on walking stability. (a) Narrow ground, (b) wide ground.

still fluctuations in stability during walking. The average trajectories of *SM*1 and *SM*2 as human walking on the ground with different slope angles are shown in Fig. 12. The results show that the values of *SM*1 and *SM*2 improve with the increase of ground slope angle, indicating the decrease of walking stability. It can be seen that when the slope angle is 10˚, the ZMP is rarely outside the support area. When the slope angle is 20˚, the probability of ZMP distributes outside the support area is increase. When the slope angle is 30˚, the ZMP often distributes outside the support area. In this situation, human can still maintain the dynamic stable walking through autogenous regulation.

4.3 The effect of contact area of support polygon on stability

The average trajectories of stability margin as human walk on the ground with different widths are shown in Fig. 13. The figures show that when walking on the narrow ground, the subjects have less stability than walking on the wide one. The ZMP is often outside the boundary of the support area when walking on the narrow ground. However, human can also quickly restore stable walking to avoid falling. The results show that the walking stability is affected largely by the contact area.

5 Conclusion

In this paper, the dominating external factors affecting human walking stability were studied. The effects of ground friction coefficient, ground slope angle and contact area of support polygon on walking stability were investigated through experiments. Considering the effects of historical stability on the current stable state, an improved walking stability evaluation method based on ZMP and STW is proposed. The new evaluation indictor *SM*2 for stability is implemented to analyze the dynamic stability. The experimental results show that the friction coefficient, slope angle and contact area all have significant effects on the gait parameters, lower limb joints motion and the walking stability. Under the influence of external environment, human can keep stable by regulating waking gait reasonably. It is observed that with the reduction of the friction coefficient, the average value of *SM*2 increases in the walking process. This indicates that the ground friction coefficient has effect on dynamic stability and the more slippery the ground is, the more instability the gait is. The experimental results also show that with the increase of slope angle, the probability of the ZMP distributed outside the support area is higher, resulting in the risk of falling down. Moreover, the size of support area is affected by the ground width. When walking on the narrow ground, the walking stability margin reduces and the gait fluctuates strongly. On this occasion, human do some posture adjustment such as stretching out arms to enhance the coronal plane stability.

As mentioned in section **2**, the improved stability evaluation method can be applied for biped robot control. The new stability evaluation method can be used as the stability indicator to modulate the trajectory of the robot joint. The experimental results of gait parameters and lower limb joints motion in this paper can be used as the modulation rule for the robot joint adjustment.

In conclusion, this paper reveals the stability mechanism of human walking and provides valuable reference to the development of biped robot. Future work will apply the proposed stability evaluation method and experimental results in this paper to actual biped control of humanoid walking.

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