Gait analysis of goat at different slopes and study on biomimetic walking mechanism

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Abstract: To study the walking status of a goat on slope and the walking mechanics, a comparative analysis of the walking gait mode of a goat on different slopes was conducted. The uphill and downhill walking processes on different slopes (6°, 18° and 36°) were recorded by a high speed video system. The experimental image results were processed and analyzed via SigmaScan software and MATLAB software. The characteristic parameters of locomotion gait on the different slopes and the angle change curves of each goat leg in the process of slope movement indicated that the goat performed tetrapod gait, static gait, ipsilateral gait and trot gait on different slopes. With the increase of gradient in the uphill process, the corresponding load factors of each leg were 0.65±0.15, 0.75 and 0.645±0.205, whereas those in the downhill process were 0.70±0.08, 0.66±0.06, and 0.685±0.125. Results showed that the load factors of each leg are higher than 0.5. The foreleg angle of α (the angle of wrist joints), which ranges from 100° to 130°, is suitable for different slopes. However, the angle of β (the angle between the thigh and the forward direction in the walking process of goat), which ranges from 99° to 109°, is suitable for the 6° slope, whereas the angle ranging from 46° to 91° is suitable for the 18° slope and 36° slope. For the hind leg, the angle of α, which ranges from 105° to 153°, is suitable for the different slopes. The angle of β, which ranges from 128° to 150°, is suitable for the different slopes. The research can provide a theoretical basis and experimental data for the design of biomimetic agricultural slope walking mechanism.

Keywords: biomimetic walking, goat gait, slope walking mechanism, agricultural robot, SigmaScan, MATLAB
DOI: 10.3965/j.ijabe.20160903.2260

Citation: Zhang F, Wang W, Zhang G Y, Wang J, Qiu Z M, Mao P J. Gait analysis of goat at different slopes and study on biomimetic walking mechanism. Int J Agric & Biol Eng, 2016; 9(3): 40－47.

1 Introduction

The rapid development of mechanization and automation has broadened the application of agricultural machinery[1]. As a large agricultural country, China is characterized by diverse topography and complex geomorphology. Hilly and mountainous areas are extensive and numerous. Such areas are featured with dispersed land, small and irregular acreage, large gap between adjacent fields, and narrow and bumpy farm roads[2]. The development of agricultural machinery has been severely constrained in the hilly areas because of the complex walking environments. Based on this, biomimetic walking mechanisms, which are suited for movement in hilly areas, would be particularly important to solve the slope walking problems of agricultural machinery in hilly and mountainous areas[2-4]. Thus, the walking mechanism was selected and analyzed in this study.

The walking mechanism is a type of robot; its

Received date: 2015-12-06 **Accepted date:** 2016-04-27
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physiological structures and motion modes imitate the movement of animals[5]. The supporting feet of this walking mechanism discretely touch the ground, and can independently choose best footholds[6]. Therefore, its trajectory is a series of isolated points. The robot is capable of active vibration isolation and can move at a higher speed on uneven ground and soft ground with less energy consumption[5-7]. Furthermore, the robot can carry out leaping motion and adapt to complex environments. Therefore, the walking mechanism has broader application prospects compared with other movement mechanisms, such as wheels, crawlers, and squirmies.

At present, different types of walking mechanisms have been researched widely; such mechanisms include one foot, two feet, three feet, four feet, six feet, eight feet, and so on. However, among these walking mechanisms, the quadruped walking mechanism has been used most widely[8-10]. Although the quadruped walking mechanism has been widely researched at home and abroad, the basic theory required for further development has not been solved[11-13]. Thus, research on the basic theory of quadruped walking mechanisms is necessary.

To study the walking status and motion rules of walking on slope, a comparative analysis of the walking gait mode of a goat on different slopes was conducted in this research.

2 Materials and methods

2.1 Experimental object

The quadruped walking mechanism has been researched widely, as well as all types of quadruped robots. However, research on robots that imitate the walking motion of goats is rare.

Goats have many advantages, including high speed and strong endurance, which enable them to run long distances. Furthermore, goats can walk on the uneven surface of the ground as well as steep and mountainous slopes; goats can freely walk in complex environments. Thus, the goat is one of the basic research objects of the gait walking mechanism. A female goat of 1.5 years old (Figure 1) was analyzed in the experiment. The main posture characteristics of the goat are shown in Table 1.

Figure 1 Photograph of the goat

Table 1 Posture characteristics of the goat

Body length/cm	Height/cm	Ratio of length and height	Weight/kg
138±0.5	90±0.5	1.53	42±0.5
Length of fore shank/cm	Length of fore thigh/cm	Length of hind shank/cm	Length of hind thigh/cm
16±0.5	30±0.5	23±0.5	23±0.5

2.2 Experimental equipment and methods

In the experiment, the three types of walkways used are those with slopes of 6°, 18°, and 36°. To ensure the same soil conditions of the different slopes, the three slopes was chosen based on the existing slopes in the experimental site and by means of inclinometers and mechanical platform scale (XSJ2×1300W-2O).

The uphill and downhill walking processes of the goat on the three slopes were recorded with a high speed video camera (FASTCAM-Super 10KC)[14-16]. The camera was limited to a maximum rate of 10 000 fps. The camera was adjusted to ensure that the photographic speed fits the goat motion on different slopes.

The motion sequence images of the three slopes recorded by the high speed video camera were stored in the computer (Intel Pentium 4 3.0 GHz). The key point data of goat physique, which refer to the respective leg knuckles and wrist joints, were collected and analyzed by SigmaScan image software and MATLAB software[17]. Then, the characteristic parameters of locomotion gait on the different slopes and the angle change curves of each goat leg during slope movement were obtained[18]. On this basis, the goat gait on different slopes were compared and analyzed.

2.3 Experimental scene

The experimental site is a hillside in the suburb of Luoyang City, Henan Province. The ambient temperature is 32-35 ℃.

2.4 Experimental procedure

The goat was pulled to walk along a straight line on the slopes to reduce the error of camera shooting and avoid processing difficulties of the image data. The entire process of goat motion was recorded by a high speed camera with a shot frequency of 10 000 fps.

The high speed camera equipment was set based on experimental purposes. The camera lens was set on the front side of the goat.

To obtain clear images of the goat, the spatial position, shooting range, shooting distance, aperture, and hardware conditions of the camera were adjusted to ensure that the main axis of the lens remains aligned with goat movement range center. The sequence images of goat walking along a straight line on the slope were recorded and stored in a computer via the memory card. The goat walking trajectories were shot completely through the method on the premise that the goat walks by itself.

2.5 Processing of experiment data

SigmaScan software and MATLAB software were used to process the experiment data. A new worksheet was established in the SigmaScan software environment. In addition, the sequence of images with a complete gait cycle was selected from the images taken during the experiment.

In the image measurement, the location of key points was described by the coordinates (*X*, *Y*), in which the value of the *X* axis direction was defined as the lateral displacement value of key points in the somatic of goat along a particular path direction. The value of the *Y* axis direction was defined as the longitudinal displacement value.

The pixel value was equivalent to the coordinate value. In addition, the maximum size of quadrant was limited by the resolution of high speed camera, which was 512 (horizontal) × 240 (vertical direction). Thus, the largest quadrant was 512 (*X* axis) × 240 (*Y* axis). The experimental data range was 0 to 512. During the goat motion process, the relative coordinate values of key points were obtained by clicking the key points of goat limbs in the sequence of images. Then, the data were saved for analysis, which is shown in Figure 2.

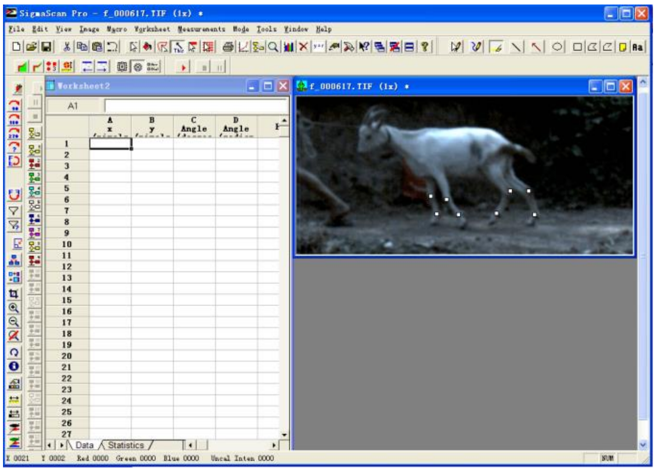

Figure 2 Joint marked point position of the goat

The obtained and saved data sequences were imported into MATLAB software. A series of corresponding characteristic curves, such as the motion curves of goat leg joints and the motion amplitude, were obtained by the above methods.

3 Comparative analysis of gait on different slopes

3.1 Comparative analysis of gait cycle on different slopes

The data for different processes and between different slopes were compared. As a result, different types of gait accounted for the proportion of the gait motion cycle (Table 2). When the goat walks on different slopes, four kinds of gait were observed, including tetrapod gait, static gait, trot gait, and ipsilateral gait. The different walking processes indicate different gait characteristics.

Table 2 Proportion of the gait motion cycle for different types of gait

Gait	6 °slope		18 °slope		36 °slope	
	Uphill	Downhill	Uphill	Downhill	Uphill	Downhill
Tetrapod gait	0	0	0	0	0	0.05
Static gait	0.70	0.79	1	0.67	0.86	0.58
Trot gait	0.11	0.13	0	0.33	0.14	0.14
Ipsilateral gait	0.19	0.08	0	0	0	0.23

The state diagrams of the complete gait cycle of each goat leg on different slopes are shown in Figures 3 to 8.

As indicated in Figure 3 and Table 2, in the uphill process of the 6° slope, the goat completed a full gait cycle in 1644 ms, and it performed the trot gait, the ipsilateral gait, and the static gait.

Figure 4 and Table 2 indicate that in the downhill process of the 6° slope, the goat completed a full gait cycle in 1832 ms, and it performed the trot gait, the ipsilateral gait, and the static gait.

Figure 5 and Table 2 show that in the uphill process of the 18° slope, the goat completed a full gait cycle in 2072 ms, and it always performed the static gait.

Figure 6 and Table 2 indicate that in the downhill process of the 18° slope, the goat completed a full gait cycle in 1568 ms, and it performed the trot gait and the static gait alternately.

Figure 7 and Table 2 show that in the uphill process of the 36° slope, the goat completed a full gait cycle in 1380 ms, and it always performed the trot gait and the static gait alternately.

As indicated in Figure 8 and Table 2, the goat completed a full gait cycle in 4004 ms in the downhill process of the 36° slope, and it performed tetrapod gait, the static gait, the ipsilateral gait, and the trot gait alternately.

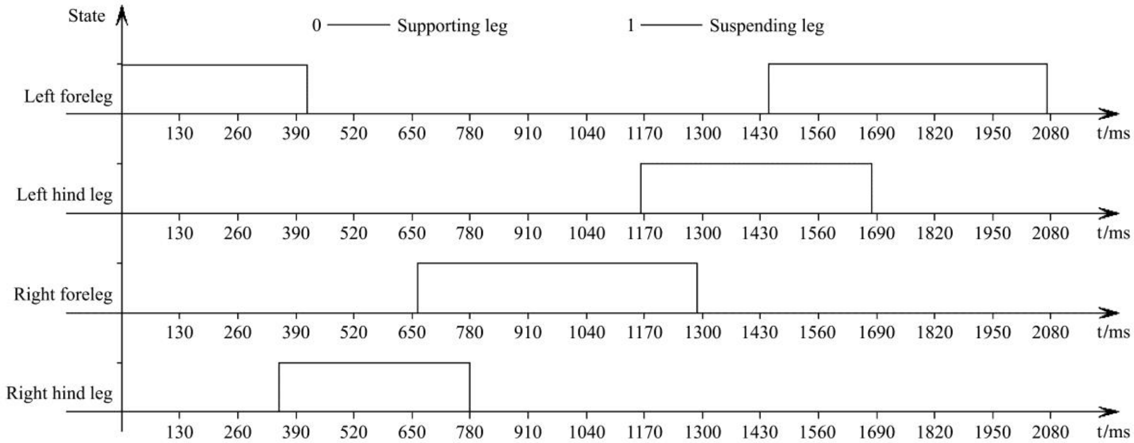

Figure 3 State chart of each leg of the goat walking uphill on 6°slope

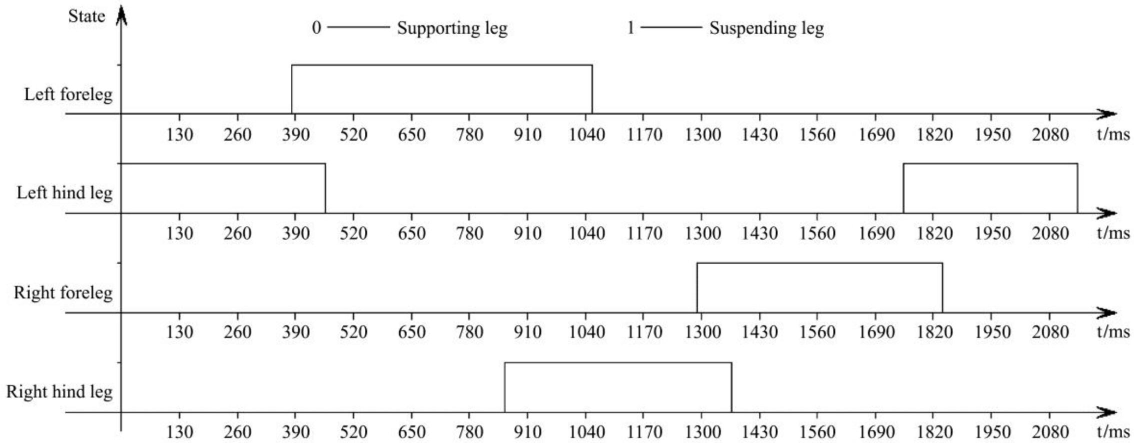

Figure 4 State chart of each leg of the goat walking downhill on 6°slope

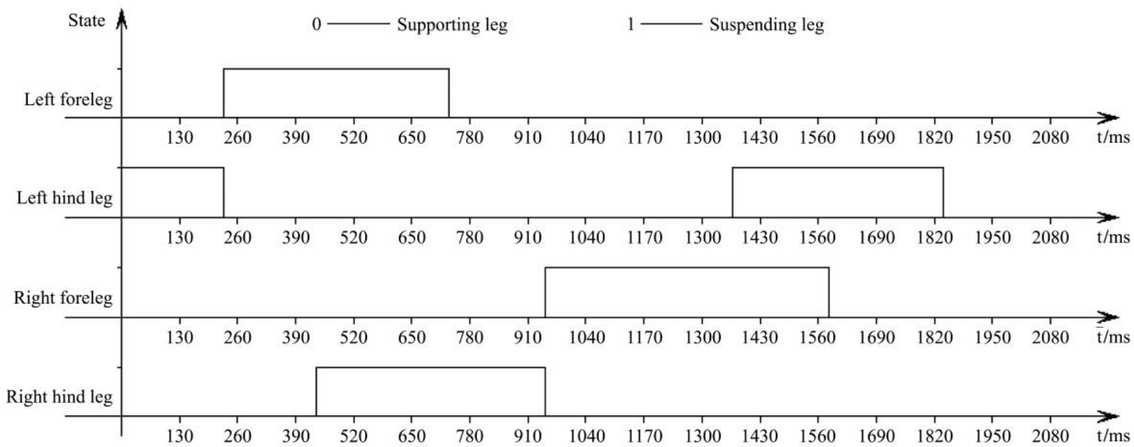

Figure 5 State chart of each leg of the goat walking uphill on 18°slope

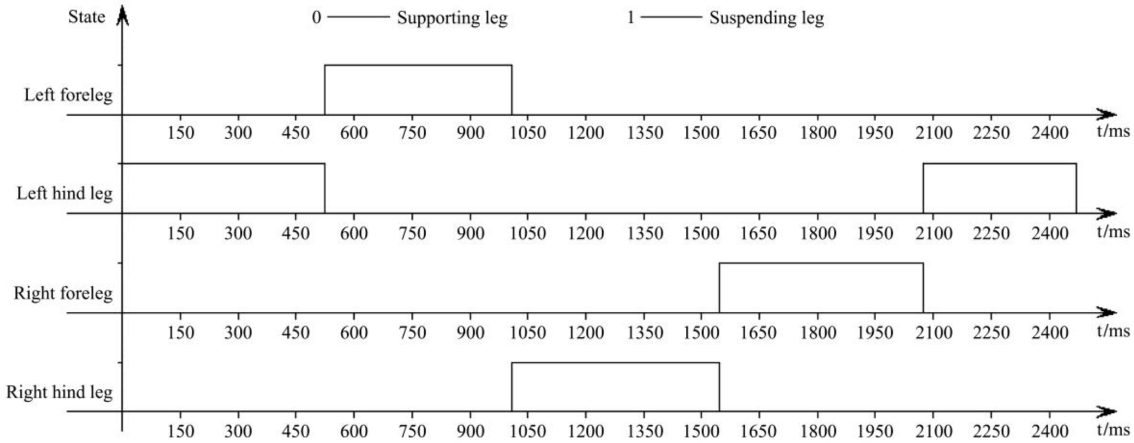

Figure 6 State chart of each leg of the goat walking downhill on 18 °slope

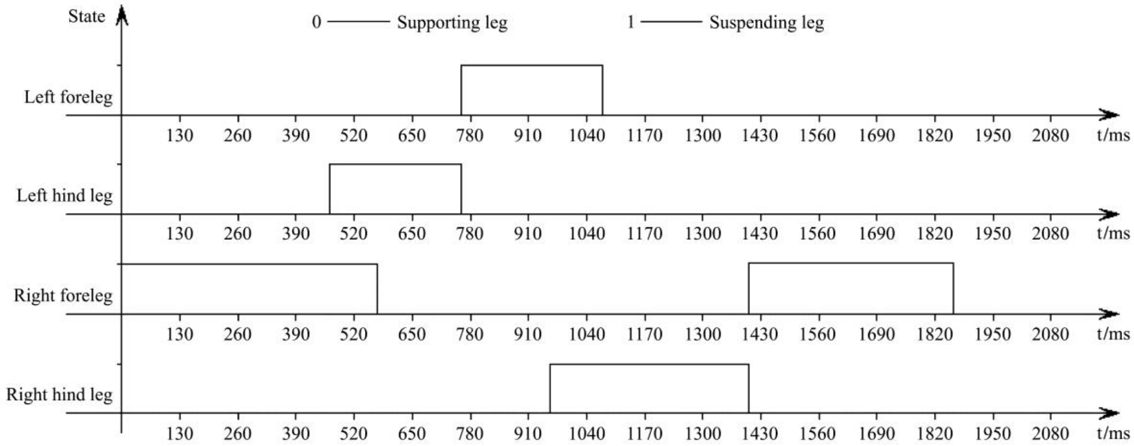

Figure 7 State chart of each leg of the goat walking uphill on 36 °slope

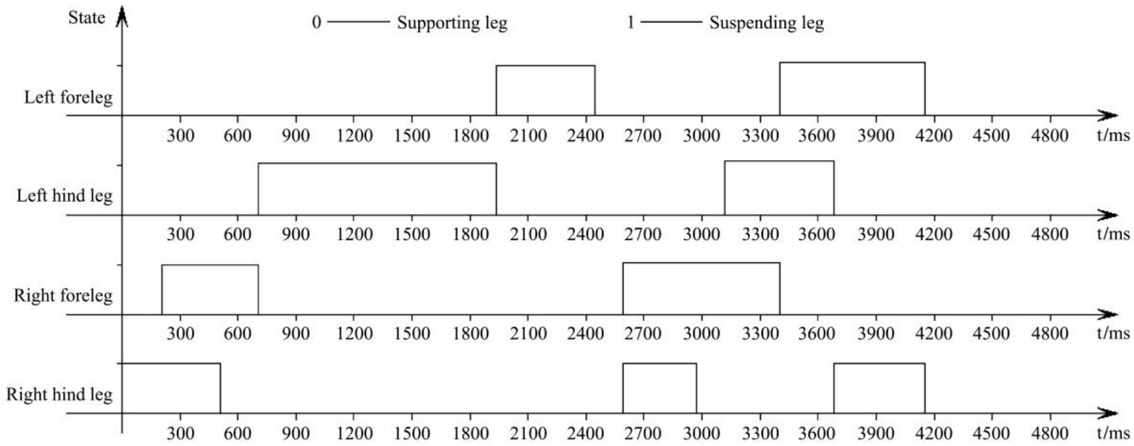

Figure 8 State chart of each leg of the goat downhill walking on 36 °slope

In a complete gait cycle of goat, the corresponding walking speed is shown in Figure 9. The figure indicates that with the increase in gradient, the walking speed in the uphill process decreases and then increases, whereas in the downhill process it increases and then decreases.

In a complete gait cycle of the goat, the corresponding walking step pitch is shown in Figure 10. The figure indicates that with the increase in gradient, the step pitch in the uphill process decreases and then increases, whereas in the downhill process it decreases successively.

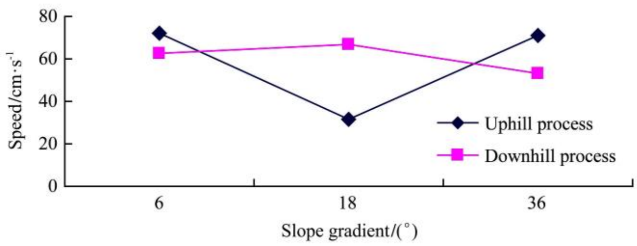

Figure 9 Speed of goat walking

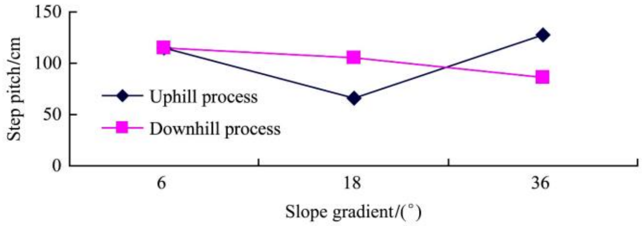

Figure 10 Step pitch of goat walking

In a complete gait cycle of the goat, the single leg span distance of the goat on the different slopes is shown in Figure 11. The figure indicates that in the uphill process, the single leg span distance of the left foreleg increases with the increase in gradient, whereas the trends of the other three legs decrease and then increase. In the downhill process, the trend of the left foreleg decreases first and then increases with the increase in gradient; those of the left hind leg and right hind leg increase and then decrease, and the trend of the right foreleg decreases.

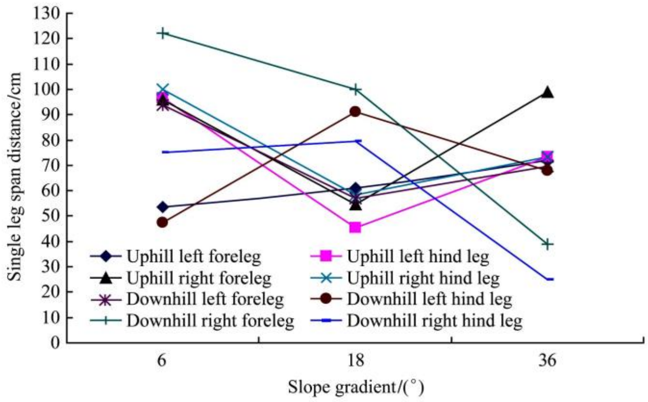

Figure 11 Single leg span distance of goat walking at different slopes

The single leg step distance of the goat on the different slopes in a complete gait cycle of goat is shown in Figure 12. The figure indicates that in the uphill process, the single leg step distance of each leg decreases and then increases with the increase in gradient. In the downhill process, the trend of the left foreleg decreases and then increases with the increase in gradient; that of the left hind leg increases and those of the right foreleg and right hind leg increase and then decrease.

The load factor of goat on the different slopes in a complete gait cycle of the goat is shown in Table 3. The table indicates that in the uphill process, the corresponding load factors of each leg on the 6° slope, 18° slope and 36° slope are 0.65±0.15, 0.75 and 0.645±0.205, respectively. In the downhill process, the corresponding load factors of each leg with the increase in gradient are 0.70±0.08, 0.66±0.06, and 0.685±0.125. The results show that the load factors of each leg are larger than 0.5; thus, the time when the leg in the support phase is longer than the time of transfer phase. Further, each leg of the goat needs more time to stabilize the center of gravity when in the support phase. In the transfer phase, each leg in the air would generate the moment of inertia. Less time for the transfer phase could reduce the effect on the goat body, which goes against the stability of body. Thus, the stability of body could be enhanced by accelerating the exchange frequency between the support phase and the transfer phase.

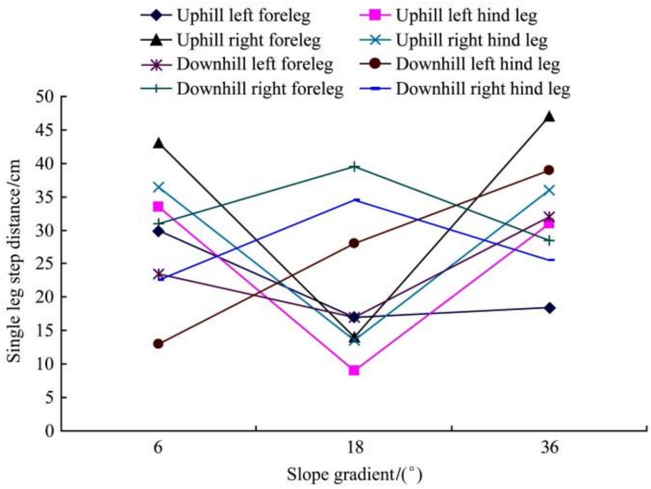

Figure 12 Single leg step distance of goat walking at different slopes

Table 3 Load factor of goat walking different slope

Slowly walking on slope	Uphill process			Downhill process		
	6°	18°	36°	6°	18°	36°
Load factor of left foreleg	0.50	0.75	0.84	0.70	0.69	0.81
Load factor of left hind leg	0.76	0.75	0.85	0.62	0.72	0.56
Load factor of right foreleg	0.52	0.75	0.44	0.75	0.60	0.81
Load factor of right hind leg	0.80	0.75	0.76	0.78	0.67	0.78

3.2 Comparative analysis of angle variation range on different slopes

The angle variation range of each leg on the different slopes in a complete gait cycle of goat is shown in Table 4. In this research, α represents the angle between the thigh and the shank in the walking process of the goat or the angle of the wrist joints. β represents the angle between the thigh and the forward direction in the walking process of goat.

Table 4 Angle variation range of each leg on different slope

Slowly walking on slope	The 6 °slope		The 18 °slope		The 36 °slope	
	Uphill	Downhill	Uphill	Downhill	Uphill	Downhill
Foreleg angle of α	98 °-180 °	43 °-130 °	100 °-185 °	70 °-181 °	80 °-180 °	74 °-179 °
Foreleg angle of β	33 °-109 °	99 °-180 °	46 °-139 °	28 °-97 °	45 °-135 °	18 °-91 °
Hind leg angle of α	105 °-163 °	85 °-153 °	103 °-169 °	97 °-178 °	84 °-167 °	70 °-172 °
Hind leg angle of β	85 °-153 °	128 °-173 °	111 °-158 °	81 °-156 °	115 °-172 °	74 °-150 °

As can be seen from the figure, for the foreleg, the angle of α, which is suitable for the 6 °slope, 18 °slope and 36 °slope, ranges from 100 °to 130 °. However, for the angle of β, which is suitable for the 6 °slope, the angle ranges from 99 ° to 109 °. To be suitable for the 18 ° slope and 36 °slope, the angle of β should range from 46 ° to 91 °. For the hind leg, the angle of α, which is suitable for the 6 °slope, 18 °slope, and 36 °slope, ranges from 105 °to 153 °. The angle of β, which is suitable for the 18 °slope and 36 °slope, ranges from 128 °to 150 °.

4 Conclusions

Gait planning is essential to biomimetic walking mechanism research. The movement and the dynamic characteristics of the machine are usually influenced by gait. In addition, implementation of the control method is affected directly by gait planning. Therefore, the goat walking experiments on different slopes should be conducted first before developing a walking mechanism to mimic goat walking process. Thus, this study analyzed the characteristic parameters of locomotion gait on different slopes and the angle change curves of each goat leg in the process of slope movement.

1) The goat performed tetrapod gait, static gait, ipsilateral gait, and trot gait on the 6 ° slope, 18 ° slope, and 36 °slope.

2) The corresponding load factors of each leg, in the uphill process on the 6 ° slope, 18 ° slope, and 36 ° slope are 0.65±0.15, 0.75 and 0.645±0.205, respectively. In the downhill process, the corresponding load factors of each leg are 0.70±0.08, 0.66±0.06 and 0.685±0.125, respectively with the increase in gradient. The results showed that the load factors of each leg are larger than 0.5. The time when the leg is in the support phase is longer than the time the leg spends in the transfer phase. These results are significant to the enhancement of the stability of a goat body.

3) For the foreleg, the angle of the wrist joints (α), which ranges from 100 ° to 130 °, is suitable for the different slopes. However, the angle between the thigh and the forward direction (β), which ranges from 99 ° to 109 °, is suitable for the 6 ° slope. The angle ranging from 46 °to 91 °is suitable for the 18 °slope and 36 °slope. For the hind leg, the angle of α, which ranges from 105 ° to 153 °, is suitable for the different slopes. The angle of β, which ranges from 128 ° to 150 °, is suitable for different slopes. The research can provide a theoretical basis for the design of agricultural walking mechanisms that can be used to adapt to different slopes in hilly and mountainous areas.

Acknowledgment

The project was supported by the Project on the Integration of Industry, Education and Research of Henan Province (Grant No. 142107000055), Natural Science Foundation of Henan Educational Committee (Grant Nos. 14B416004, 14A416002 and 13A416264), and Innovation Ability Foundation of Natural Science of Henan University of Science and Technology (Grant No. 2013ZCX002).

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