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Do humans walk like robots when crossing an obstacle without visual information?

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Abstract—.**This work analyses the obstacle crossing during gait and compares the behavior of humans with a robot model. The aim of the study is to compare the obstacle crossing task between human subjects, performing the task both with vision and blindfolded, and ZMP biped robots. It was hypothesized that the trajectories of the hip joint and the foot of the blindfolded subjects would resemble those of the robot. Seven subjects walked on a flat surface with an obstacle of 0.26 m height and crossed the obstacle successfully 30 times under two conditions: blindfolded and with normal vision. The motion of the leading limb was recorded by video at 60 Hz. There were markers placed on the subject's hip, knee, ankle, rear foot, and forefoot. The following parameters were calculated: critical time, vertical foot position and average step velocity. A robot model with inertial parameters matched with the subjects and a controller based on the ZMP criterion was developed. The hip joint and foot trajectories of humans and robots were assessed and compared. Unavailability of visual information resulted in different strategies to cross the obstacle, like a higher toe clearance or lower step speed. Without vision, the crossing pattern seems to be more cautious and slower than with vision, thus resembling that of the robot with ZMP. The hip was kept behind until the foot has overtaken the obstacle as a possible mechanism to maintain a safe base of support if a trip occurs. This is also supported by the data showing that blindfolded behaved with an intermediate pattern between vision and robot in the hip antero-posterior trajectory. In this context, it is possible to extract some conclusions to improve the ZMP stability criterion of biped robots.**

I. Introduction

The control of locomotion in humans depends heavily on visual information [1]. Visual perception allows the subject estimate the physical properties of the environment [2] and is crucial to elaborate and update dynamic spatial maps that favor safety during locomotion [3].

In this context, crossing obstacles safely and efficiently requires proprioceptive and visual information about the environment that is varying [4]. In the absence of visual information, sighted individuals can recover relevant information from the environment to perform obstacle crossing possible [5]. Nevertheless, there are differences in the motion patterns used in the execution of the task.

The control of lead limb elevation during an obstacle crossing task seems to be mainly feedforward and based on prior information about the obstacle height and position. This information could be provided either by the visual or haptic system. Feedback control based on visual information about limb position and movement can be used to fine-tune the trajectory [6]. Accuracy of the foot clearance, measured by horizontal and vertical distances between foot and obstacle is related to the ability of generating accurate spatial maps based on exteroceptive sensory information about obstacle height and position [7].

Previous studies have shown that human subjects, when blindfolded, present several changes in the obstacle crossing patterns with respect to performing the same task with vision [8]. These differences, that can be described as a "more cautious pattern" for the people blindfolded, resulted in slower set speed and higher foot clearance [8]. It has been suggested that the task is performed with the foot more advanced than the body center of mass, thus allowing a reduction of the forward speed and preparing for a more conservative lowering strategy in the case of a trip [8-10].

On the other hand, biped robots that walk using Zero Moment Point (ZMP), present gait speeds that are slower than human gait. These robots walk advancing the leg, securing a base of support before advancing the body and the same strategy based on the ZMP is used to cross obstacles.

The aim of the present study is to compare the obstacle crossing task between human subjects, performing the task both with vision and blindfolded, and ZMP biped robots. It was hypothesized that the trajectories of the hip joint and the foot of the blindfolded subjects would be very similar to those of the robot. Therefore, when crossing an obstacle deprived from vision, humans should rely in a model to control the task that could resemble the ZMP concept.

The paper is organized as follows, in Section II the Methods are presented, including the experiments with humans and the model of the robot used to generate the trajectories. Section III describes the results where the kinematic patterns of the leading limb during obstacle crossing are compared between the different groups, vision, blindfolded and robot. Section IV presents the Discussion of these results in the context of human behavior and the control of biped walking robots.

II. Methods

A. Experimental protocol

Seven volunteers with normal vision participated in this experimental study. In Table 1 the age, height and weight of the participants are presented. The experiments were conducted according to the ethical guidelines of the São Paulo state University (UNESP) Every volunteer signed an informed consent before participating in the tests.

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Table 1 Physical characteristics of the participants. These values were used to model the subjects characteristics.

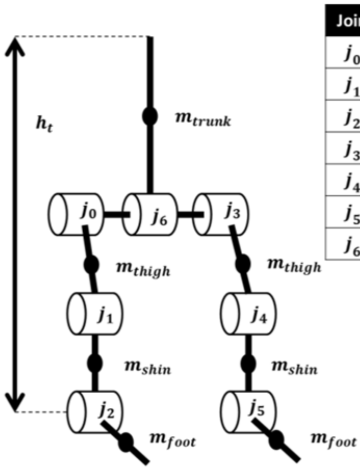
Subject	Age (Years)	Height (m)	Weight (kg)
AB04	42.0	1.70	75
AB05	18.2	1.75	57
AB06	26.9	1.71	75
AB07	53.2	1.70	74
AB08	46.7	1.85	91
AB09	40.3	1.72	86
AB10	47.8	1.74	77

The seven subjects walked along a five meter flat pathway (approximately 0.2 m above floor level) with an obstacle of 0.26 m height located at 3 m from the starting point. They crossed the obstacle successfully 30 times in two conditions: blindfolded and with normal vision (eyes opened). Gait speed was self-selected. The motion of the leading limb was video recorded at 60 Hz. Five markers placed on the leading limb at the following anatomical locations: hip (greater trochanter), knee (lateral epicondyle), ankle (lateral malleollus), rearfoot (calcaneous tuberosity), and forefoot (fifth metatarsal joint).

B. Robot model

A robot model along with a controller based on the ZMP criterion was developed in Matlab (The Mathworks Inc.) environment. With respect to the mechanical configuration of the biped robot it as chosen a seven links planar model. The links represented the trunk, two thighs, two shins and two feet. These links were joined by hinge joints representing the hip, the knee and the ankle joints.

In order to match a robot model with each one of the human participants we used the height and the mass of the subjects to define the inertial parameters of a robotic counterpart. The segment masses and dimensions of the robot models were then scaled following the parameter given by Winter [11]. The described model is ilustrated at Figure 1.



Joint	a_i	d_i	α_i	θ_i
j_0	0	0	$0.245h_t$	θ_0
j_1	0	0	$0.246h_t$	θ_1
j_2	0	0	$0.122h_t$	θ_2
j_3	0	0	$0.245h_t$	θ_3
j_4	0	0	$0.246h_t$	θ_4
j_5	0	0	$0.122h_t$	θ_5
j_6	0	0	$0.509h_t$	θ_6

m_i	Value
m_{thigh}	$0.1b_m$
m_{shin}	$0.0465b_m$
m_{foot}	$0.0145b_m$
m_{trunk}	$0.678b_m$

$b_m = Body\ Mass$

Figure 1. Robot Model

The robot joint trajectories were derived from both the COM and the swing foot trajectories with a numerical inverse kinematics algorithm. The COM trajectory was generated using quadratic programming in order to keep the ZMP inside the support base as described by Wieber [12].

The prescribed swing foot trajectory was defined with a constant speed in the antero-posterior direction. The vertical trajectory was described with a sine function in order to decelerate the foot at landing and avoid high impacts.

C. Data processing

The motion data were filtered with a fourth order Butterworth filter with a cut-off frequency of 4 Hz. In this way the antero-posterior and vertical trajectories of the joints were obtained.

The following parameters were obtained from the motion data in order to assess the differences between the vision and blindfolded experimental results:

- Critical time: the instant when the foot crosses the obstacle given as a step percentage.
- Vertical foot position at critical time.
- Average step velocity of the leading limb stepping over the obstacle (dividing step length by step duration).

In order to test the effects of visual availability, data from each variable above were submitted to a t-test comparing the vision and the blindfolded groups. The significance level adopted was 0.05 for all analyses.

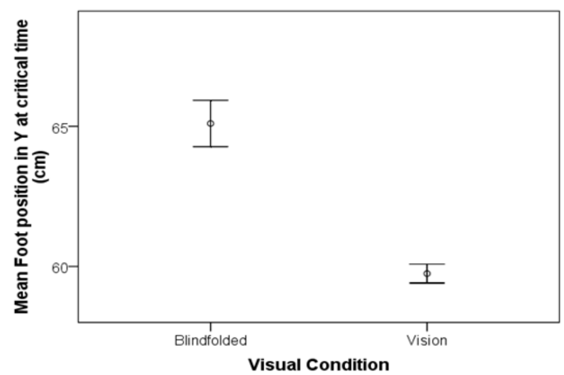


Figure 2. Mean and 95% confidence intervals of the vertical foot position obtained during the experiments with subjects grouped, respectively, in the blindfolded and vision conditions.

The trajectories of the different joints of the human volunteers while performing the first trial under the two vision conditions (with vision and blindfolded) were plotted together with the results from the simulation of the matched robotic model. Only the first trial was chosen in order to avoid the possible influence of adaptation during the consecutive 30 trials.

The hip-foot distances in the antero-posterior and vertical directions were obtained by subtracting the position of the leading foot and the hip. As the foot is always ahead of the hip, during the obstacle crossing, it results in a positive value in the antero-posterior direction. However, in the vertical direction the hip is always higher that the foot, thus resulting in negative values for this parameter.

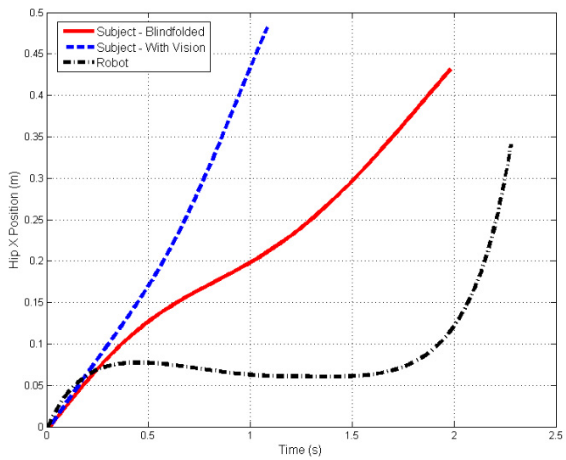


Figure 3. Hip position trajectories vs time in the antero-posterior direction (X coordinate) performed by the human volunteers with vision (dashed line), blindfolded (solid line) and the robot model (dash-dotted line). The results correspond to the first trial of a representative subject.

III. Results

Critical time, vertical foot position at critical time and average step velocity showed statistically significant differences between the blindfolded and vision conditions.

Blindfolded participants crossed the obstacle earlier, with a higher vertical foot position and lower step velocity than participants with vision. Fig.2 shows the mean and 95% confidence interval bars of the vertical foot position.

Fig. 3 shows the antero-posterior trajectory of the hip joint during the crossing of the obstacle. With vision, the hip advanced at a constant speed.

In the blindfolded condition, the subject reduced the speed while the robot stopped until the instant when the foot is about to touch the ground.

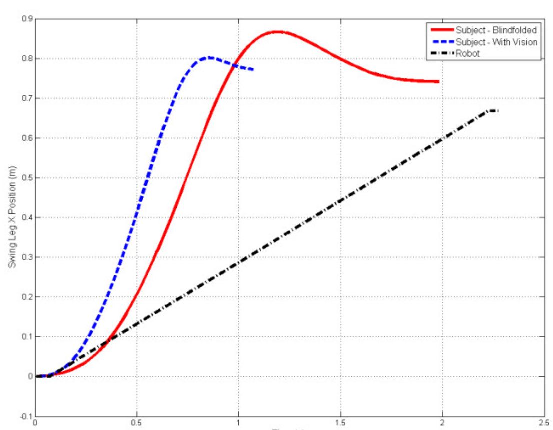


Figure 4. Foot position trajectories vs time in the antero-posterior direction (X coordinate) performed by the human volunteers with vision (dashed line), blindfolded (solid line) and the robot model (dash-dotted line). The results correspond to the first trial of a representative subject.

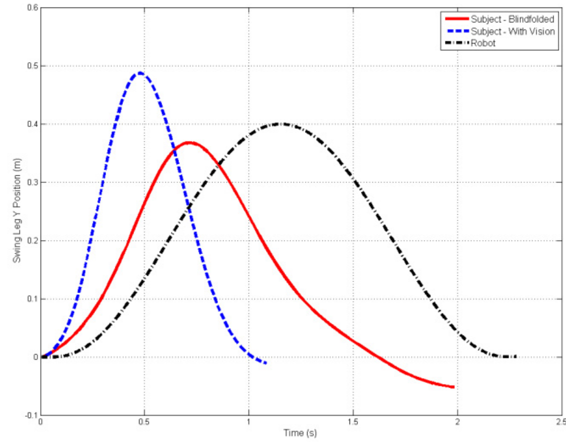


Figure 5. Foot position trajectories vs time in the vertical direction (Y coordinate) performed by the human volunteers with vision (dashed line), blindfolded (solid line) and the robot model (dash-dotted line). The results correspond to the first trial of a representative subject.

The blindfolded condition represented an intermediate hip trajectory between the vision and the robot trajectories. Moreover, in the absence of vision and in the robot model, the step duration is larger, in agreement with a significantly slower step speed.

The results in Fig. 4 and Fig. 5 show the measured vs the imposed trajectories on the foot of the robot model as a function of time. The antero-posterior foot trajectory of the robot model was defined as a constant speed with a linear relation between the start and end points. It can be noted that humans, either with vision or blindfolded showed a different pattern. The vertical trajectories of the foot as a function of time are presented in Fig. 5. The foot trajectory of the robot was defined by a sine function in order to reduce the foot speed before contact. In this case the sinusoid matches the human behavior.

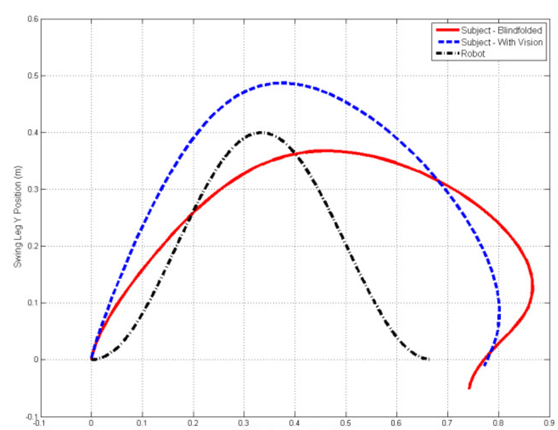


Figure 6. Foot X-Y position trajectories vs time in the antero-posterior direction (X coordinate) performed by the human volunteers with vision (dashed line), blindfolded (solid line) and the robot model (dash-dotted line). The results correspond to the first trial of a representative subject.

Fig. 6 shows the distance between hip and foot normalized to the maximal distances of the vision conditions. The antero-posterior distance is plotted against the vertical distance. The horizontal distance between the hip and the foot is smaller for the subject with vision than for the blindfolded and the robot.

The vertical distance between hip and foot of the robot model had a pattern that was different from that of the human subjects. It can also be noted the pendulum behavior of the legs of the humans (for both conditions) in contrast with the trajectory of the robot leg.

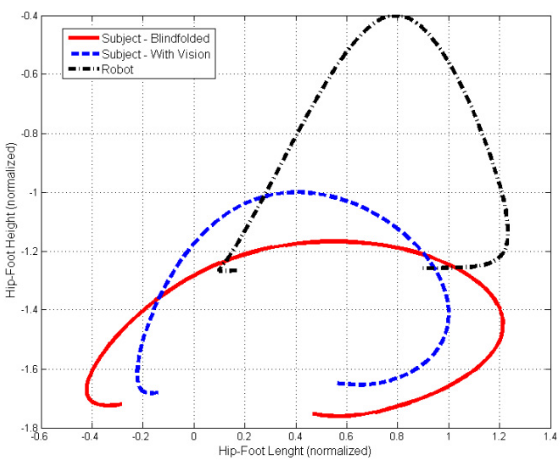


Figure 7. Hip-Foot position trajectories in the antero-posterior (X coordinate) vs vertical axis (Y coordinate) performed by the human volunteers with vision (dashed line), blindfolded (solid line) and the robot model (dash-dotted line). The results correspond to the first trial of a representative subject.

IV. Discussion

This study has analyzed and compared the obstacle crossing task between human subjects, performing the task with vision and blindfolded, and ZMP biped robots. The original hypothesis about the similarities between the blindfolded subjects and the robot model was partially confirmed. Therefore, when crossing an obstacle deprived from vision, humans rely in a model to control the task that is more similar to the ZMP concept. However, there are other mechanisms that influenced the responses of the human subjects. Even deprived from vision advanced their hip with the foot unlike the robot that kept the hip behind to comply with the ZMP stability criterion, see Fig. 7.

Unavailability of visual information resulted in different strategies to cross the obstacle, like a higher toe clearance or lower step speed [5, 7, 13]. The step speed when crossing the obstacle is reduced without vision. In this case, subjects must rely on their internal models of the environment and proprioceptive information. It appears that without vision the crossing pattern seems to be more cautious and slower than with vision, thus resembling that of the robot with ZMP.

The antero-posterior distance between the hip and the foot reached, for the blindfolded subject and the robot, similar peak values. This could reflect a more conservative strategy in terms of avoiding a trip and fall than the humans walking without vision. On the one hand, increasing foot clearance aims at guaranteeing trip avoidance.

On the other hand, keeping the hip (and the body center of mass) behind until the foot has overtaken the obstacle could be a mechanism to maintain a safe base of support if the foot hits the obstacle and a trip occurs. This could be a conservative strategy in the sense that the hip is not displaced until a new stable base of support can be formed when the leading foot reaches the ground. This is also supported by the data showing that blindfolded behaved with an intermediate pattern between vision and robot in the hip antero-posterior trajectory. The possible explanation to this could be a minimization of the risk of falling if a trip occurs. It was reported in the literature that late swing trips tend to elicit lowering recovery strategies [9, 14]. In this strategy, the foot that contacts the obstacle is brought immediately to the ground. Therefore, advancing the swing foot while the hip is kept behind allows a larger margin to reduce the forward gait speed [10].

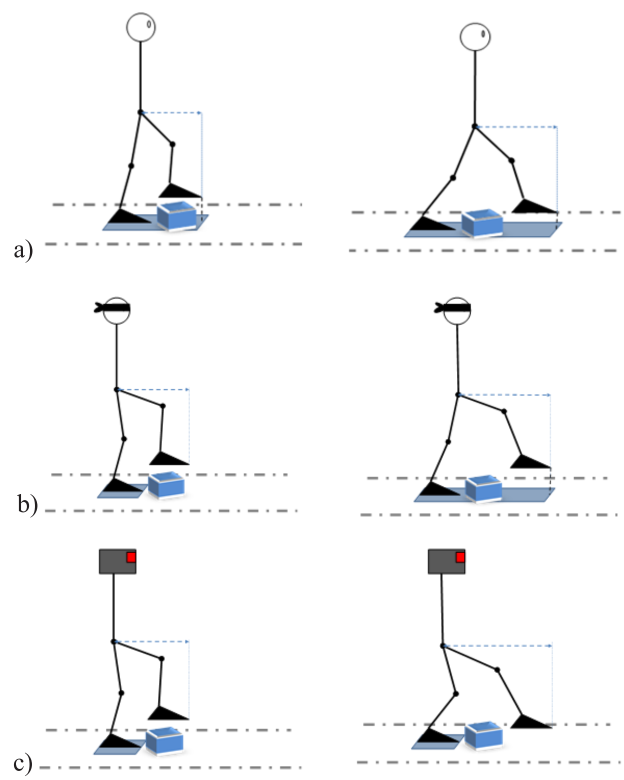


Figure 8. Diagram of the obstacle crossing task for a) humans with vision b) humans blindfolded and c) robot model with ZMP stability criterion

Nevertheless, this strategy not only results in lower speeds, but also in larger energy consumption due to acceleration and deceleration of the hip. The extreme case would be the ZMP robot that stops completely the hip antero-posterior motion and afterwards it has to accelerate it. In contrast blindfolded subjects moved the hip forward at a lower speed than subjects with vision. Probably they keep a certain ratio between the positions/speeds of the leading foot and the hip.

Recent work has shown experimentally the need of visual information several steps ahead in order to walk over obstacles in a successful and efficient manner [15]. During the swing phase of gait, the mechanics of the human body behave as an inverted pendulum, explaining the large energy consumption differences between humans and robots in biped gait [16]. In this respect, major energy exchanges occur during the double stance phase of gait, while the swinging leg behaves almost passively with the initial conditions for the motion are set at toe-off [16, 17]. If vision was restricted to less than two steps ahead, it was not possible to adjust both the foot placement and the push-off forces to take advantage of this inverted pendulum dynamics [15]. In our experiments, as the subjects are without vision, the obstacle crossing task is not performed keeping the inverted pendulum dynamics, much like robots following the ZMP stability criterion.

These results underscore the multifactorial aspects of an obstacle crossing task during gait to perform safely the task while maintaining the energy consumption as low as possible. In this context, it is possible to extract some conclusions to improve the ZMP stability criterion of biped robots. In addition, future research expanding the model to three dimensions and completing an energy analysis is being carried out.

V. Conclusion

This analysis revealed significant differences between the vision and blindfolded conditions in healthy subjects.

These results indicate that vision is crucial to determine the optimal trade-off between energy consumption, trip avoidance and risk of a fall during obstacle crossing. Further work is guaranteed to unveil the model that explains this multifactorial optimization and the possible application to biped robots.

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