Local path planning during locomotion over irregular terrain

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Abstract

We have been exploring the factors that guide the selection of alternate foot placement during locomotion in a cluttered environment. The results show that when normal landing area is unavailable or undesirable, individuals select an alternate foot placement that minimizes changes to the normal gait trajectory and ensures dynamic stability. These experiments shed light on fundamental issue of local path planning and are relevant to the design of legged robots designed to function in an unstructured environment.

1. Introduction

Path planning is an integral component of locomotion, and most often refers to route plans to goals that are not visible from the start. The choice of a particular travel path is dependent on a number of factors such as energy cost (choosing the shorter of possible paths) and traversability (choosing a path that has been selected and traversed by others) [1]. We consider this global path planning. The focus of this paper is on adjustments to gait that one routinely makes to avoid stepping on or hitting undesirable surfaces, compromising dynamic stability, possibly incurring injuries. These on-line adaptations to gait termed local path planning, include selection of alternate foot placement, control of limb elevation, maintaining adequate head clearance and steering control [2], [3]. This is a hallmark of legged locomotion making it possible to use isolated foot holds for travel [4]. We have been exploring the factors that influence local path planning in several experiments and show that visual input alone does not specify a unique action: other factors play a role in decision making. The focus of the experiments was determining what guides the selection of alternate foot placement during locomotion in a cluttered environment.

In the first series of experiments, individuals were instructed to walk and avoid stepping on a light spot should one appear in the travel path [5]. The position and shape of the light spot was varied such that if an alternate foot placement is not chosen, the normal foot landing would cover different portions of the light spot. The available response time was varied and alternate foot placement chosen were categorized into one of eight choices. The results showed that selection of alternate foot placement was systematic; there is a single dominant choice for each combination of light spot and normal landing spot. A hierarchy of rules was derived from the choices made by the individuals (see Figure 1). First, the selection minimized the displacement of the foot from its normal landing spot. Second, if more than one choice met this criterion, alternate foot placement in the plane of progression was preferred. When there was a choice between stepping long versus short, stepping long was preferred; when there was a choice between stepping inside versus outside, stepping inside was preferred. Analyses of the choices made revealed that the dominant choice requires minimal threat to dynamic stability, allows for a quick initiation of change in ongoing movement and ensures that the locomotor task runs without interruption. These apriori criterion and constraints on the decision making clearly suggests that perception-action coupling mediating foot positioning is dependent not only on visual input acquired by the moving body [6], [7], but also on the prediction of future foot placement from kinesthetic input and constraints posed by dynamic stability requirements.

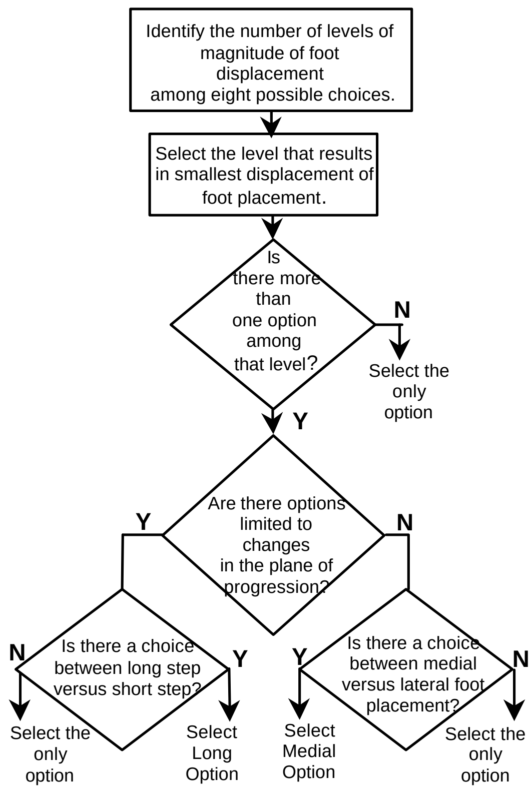

Figure 1: Decision tree that guides foot placement choice developed from experimental data from Patla et al. [5].

2. Computer Simulation of the Adaptive Locomotor Task: Experiment 1

Dynamic stability and ongoing locomotor demands are, we argue, the primary reasons why the control system satisfies the objective and constraints in its selection of alternate foot placement. To indirectly test this reasoning, we decided to keep the perceptual part of the task similar, while changing the action part. Action required in this case involved the use of upper limbs to generate the response, significantly altering the postural/balance requirements. Basically we used the famous yellow pages directory dictum to “let the fingers do the walking”.

2.1 Participants

Ten healthy participants with no known neuromuscular pathologies volunteered for the study. Age - mean - 20.1 yrs; range - 18-25 yrs; Gender 5M, 5F; 9 right handed and 1 left handed evaluated using a questionnaire by Bryden [8].

2.2 Computer Simulation of Locomotor Task

A customized program was written to show top view of a travel path on the computer screen. Footprints were shown to travel from the bottom of the screen to the top. In 50% of the trials a light spot was projected where the 4th step would normally land. The trigger for the light spot was the previous foot contact thus giving subjects one step duration to plan and manually move the next foot placement to an alternate location. The light spots were similar in shape and size (with respect to the footprint on the screen) to those used in the previous two locomotor experiments.

2.3 Protocol

Participants were comfortably seated in front of the computer screen and shown sample computer walking trials. They could control the foot placement by a mouse. The mouse was positioned at a comfortable distance and location aligned to the midline of the body. They completed a set of trials with right and left hands. The sequence of right and left hand were randomly assigned.

2.4 Data Analyses

The analysis was identical to the one carried out for the previous experiment by Patla et al. [5].

2.5 Results

There were some small differences in the responses between left and right hand, but in both instances the response choices did not match with those observed in previous experiments. We focus on the responses for the right hand since in the locomotor experiment subjects altered the right foot placement. Chi-square analyses revealed no significant differences in the dominant foot placement for the six experimental conditions (see Figure 2). It is clear from Figure 2 that the dominant response is medial displacement of the footprint, by moving the mouse towards the midline of the body. Success rates for avoiding the light spot were high (98% or greater).

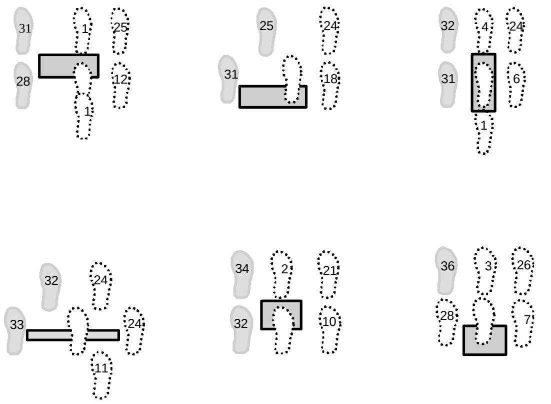

Figure 2: Results of foot placement choices from Experiment 1. Shaded rectangle area represents landing area to be avoided. Foot print location show the landing area chosen by the individual; the shaded footprint represent the dominant choices made by the participants.

2.6 Discussion

It is clear that the dominant responses observed in the computer simulation of the adaptive locomotor task are not the same as those seen in previous experiments. The mouse movement required to avoid the light spot are similar to the operations performed in a graphical computer environment such as dragging a file into the trash can. This file dragging operation has been found to be faster than other ways to perform the same task [9].

What is intriguing is that the dominant response among all the conditions involves movement of the mouse leftward or upward and leftward. Elliott et al [10] have shown that movement adjustments required to point to a target that is perturbed to the left are faster than when the target is perturbed to the right. They have attributed this to different roles of the two cerebral hemispheres. It should be noted that both dominant responses in this study (movement of the mouse to the left or left and upward) involve simple control at a single joint (shoulder rotation for movement to the left which could also be initiated with the wrist and shoulder flexion for movement to the left and upward).

The lack of differential dominant responses for the six experimental conditions clearly suggests that postural/balance constraints, the effector system (upper limb versus whole body) and the ongoing movement/posture used have a tremendous influence on the outcome.

3. Selection of Foot Placement under no time or spatial constraints: Experiment 2

The previous studies where individuals were constrained to modify their steps following a visual cue were useful in elucidating the criteria people use in selecting an alternate foot placement under time and spatial constraints. In other studies of adaptive locomotion, individuals are given the choice to modify their approach phase to step on a target. [11]; [12]); only the goal was specified, not how it was achieved. The changes required in the stepping patterns in these studies were restricted to the plane of progression and the results show that individuals modulate their step length in the last three steps to ensure stepping on the take-off line for a long jump [11]. What would happen to the foot placement selection to avoid landing on a target, if individuals had the freedom to modify their approach phase. An experiment to answer this question was developed and is described next.

3.1 Participants

Twelve healthy participants (6 males and 6 females) with no known neuromuscular pathologies volunteered for the study. (Age - mean - 24 yrs; range – 21-33 yrs). The average step length was 70.8 cm (range 59-78.9 cm), and the average step width was 23.2 cm (range 16-30 cm).

3.2 Schematic of the experimental setup

The top view of the travel path is shown in Figure 3. The rectangles represented possible landing targets and were adjusted to each individuals normal step length. A possible landing target was white in color, whereas a red rectangle represented a landing target to be avoided. A red rectangle was placed at the location indicated by the darkly shaded rectangle, and another one was randomly placed in one of the lightly shaded rectangle.

3.3 Protocol

First, to determine step length and step width, all the participants were asked to walk across a black rubber mat with chalk on the soles of their shoes. Average step length and step width were calculated from four consecutive steps on the mat. Based on the individual measures, a 9.0m pathway of white targets (dimensions 28cm x 14cm) was set up. The white targets were placed medially, laterally, anteriorly, and posteriorly to the participants' expected foot placement. Participants were instructed to walk across the

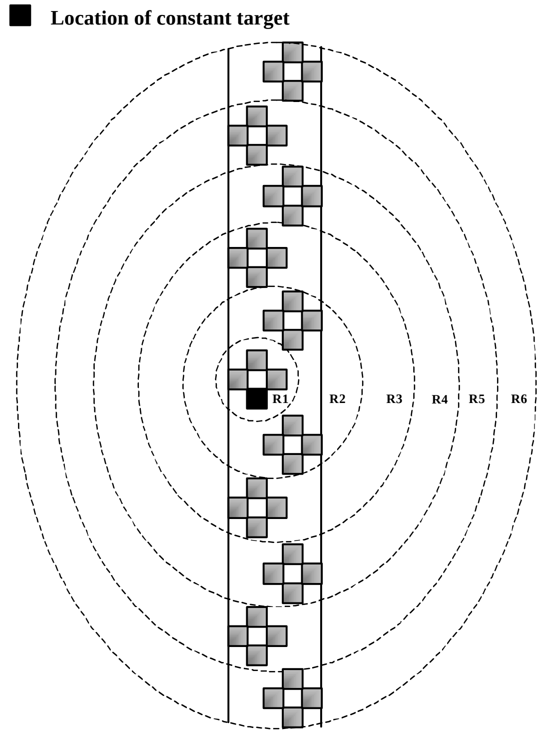

Figure 3: Schematic diagram of the travel path for Experiment 2. Each of the shaded rectangle area represents a possible landing target. A white rectangle in the shaded area represents a target area that can be stepped on, while a red rectangle represents a landing area that has to be avoided. One red rectangle was located in the area shown by the darkly shaded rectangle. The other red rectangle was located randomly in one of the other shaded rectangles

pathway, starting with the right leg and stepping on the white targets only, avoiding the red ones. No other specific instructions regarding where to step were given. There were a total of 55 trials for each participant, 10 of which were control (no red targets in the pathway). A video record of each walking trial was obtained.

3.4 Data Analyses

From the video records, the following measures were determined. Each step was coded with respect to the other foot placement as normal, long, short, medial, lateral or any combination of those. Next, the data was transcribed into x-z co-ordinates system and graphed according to the following convention: in the x-direction, short step was –1, long step was +1; in the z-direction: medial step was –1, lateral step was +1. Figure 4 shows an example of the changes in step length and width in a given trial for three different participants.

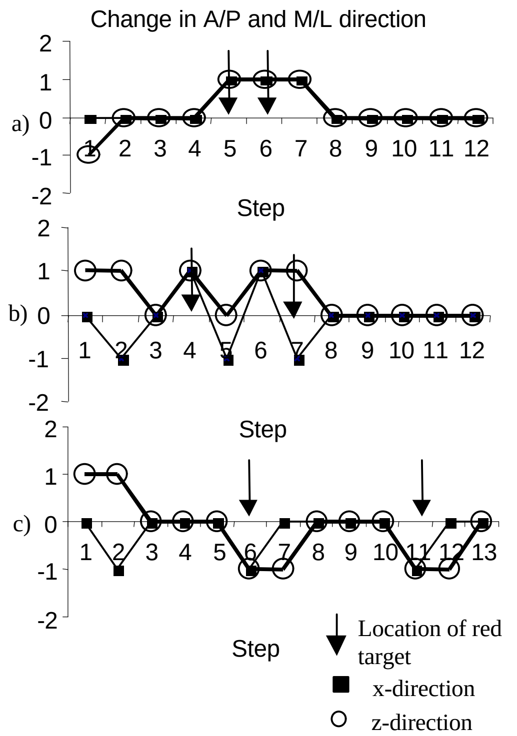

Figure 4 a, b, & c: Stepping pattern of three participants for selected trials.

3.5 Results

The following key results were obtained. Maximum number of consecutive steps modified during a given trial were either 1 (22.9 %) or 2 (68.3 %). The relative location of the two targets that were to be avoided had no effect on whether or not one or two consecutive steps were being modified as shown in figure 5. Greater than 80% of the steps in all the trials across all participants were of normal step length and width. Majority of the adjustments in step length (99 % of the total number) was equal to about an average foot length (28 cm); while majority of step width adjustments (93 % of the total number) was restricted to about an average foot width (14 cm).

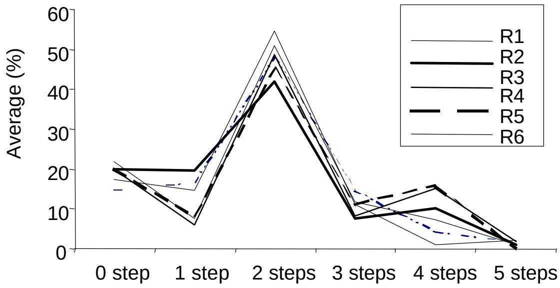

Figure 5: Average % of step modifications if the random target was located within a given radius of the constant target.

3.6 Discussion

These results confirm the findings of previous studies. Individuals do minimize the displacement of the foot from its normal landing spot (selection of stepping wide or narrow). Minimizing the changes to the normal walking patterns ensures that the energy cost for travel is minimized [13], and also reduces the demand on the postural/balance control system [5]. Adjustments to gait patterns are predominately in the plane of progression (almost equal number of step length changes compared to step width changes even though the step length changes are two times the step width changes). Changes in the step metrics in the plane of progression involve modulation of active muscles that are normally very active [14]. In contrast, changes in the step metrics in the frontal plane (step width modulation) require activation of muscles that are not as active [14]. In addition these results do show that adjustments to the stepping patterns are localized to one or two steps, and individuals do return to their normal gait patterns during subsequent steps. These findings are also similar to the observations by Lee et al. [11] that individuals limit the changes to a few steps to ensure that the goal of avoiding or accommodating a landing target for foot placement in the travel path.

4. Conclusions

We have been able to identify the objective and constraints that guide the selection of alternate foot placement during locomotion. Selection of alternate foot placement is not random; there is a single dominant choice for each situation which offers several advantages. The dominant choice requires minimal changes to the ongoing locomotor muscle activity, poses minimal threat to dynamic stability, allows for quick initiation of change in ongoing movement and ensures that the locomotor task runs without interruption. Perception-action coupling mediating this task is dependent not only on visual input but also on prediction of future foot placement and on constraints posed by dynamic stability requirement. Since they are subject to the same perceptual locomotor constraints, the results from these studies would be useful in the design of bipedal robots.

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6. Acknowledgements

This work was supported by a grant from NSERC Canada.