Foot Placement for Balance with Waist-pull Perturbations
Delivered While Standing

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Keywords: Push recovery, Step strategy, Biped system.

Abstract. Stepping is one important strategy to restore balance against external perturbations. Human walking exhibits step variations in both step position and step duration, some of which may be related to the magnitude of perturbations. Here, we conduct balance recovery experiments with 10 subjects, on which waist-pull perturbations are implement during standing. Their recovery step positions and step durations are measured under various perturbations. Results show that step duration is concentrated in a small range and step position has a positive correlation to the magnitude of perturbations. It indicates that for human walking, the optimal step duration for push recovery keeps constant under various perturbations, but optimal step position increases linearly with the magnitude of perturbations. These results provide insight regarding the balance control of biped system in planning its foot placement.

Introduction

Avoiding falls is a primary issue in legged locomotion. Not only may it damage a legged system or robot, a fall will disturb its surroundings as well. It is desirable that bipedal systems can restore balance from perturbation rapidly and efficiently. Previous research has presented various strategies to recover balance [1], but one promising method is to take a step to avoid a fall, especially for a large magnitude push [2, 3].

To keep a static standing without falls is one of primary locomotion tasks, not just for creatures, like human beings, but also for humanoids. It has been reported that perturbations to biped system can be partly corrected by adjusting its foot placement on the next step [4]. However, the principle by which step duration and position are decided under perturbations has not been clearly explained.

Some experimental results have shown that different magnitudes of external perturbations produce the diversity of influences on recovery steps [5, 6]. Moreover, it has been shown that people who encounter with large perturbations or live with aging leg muscles, prefer to take more than one step for balance, especially with two steps [7, 8]. Related studies developed a comprehensive numerical tool capable of predicting the outcome of a balance perturbation [8, 9].

Dynamic stability in bipedal locomotion and prediction models have been proposed to predict recovery steps [10 - 12]. Pratt et al. presented a notion of the capture point, the point on the ground where the robot can step to achieve a full stop; capture region is the set of capture points [13]. Based on the well-known Linear Inverted Pendulum Model (LIPM), Koolen et al. [14] introduced capturable regions and presented a capturability-based algorithm to control a humanoid robot M2V2. For both stationary standing and walking tasks, Zaytsev et al. [7, 15] generalized the concepts of capturable region to execute a desired locomotion motion. Although above literatures demonstrated the range of predicted step position on the ground for balance recovery, these predictions mainly depend on the analysis of support leg dynamics. However, stepping for balance is not just related to step position, but closely to swing leg dynamics, which possibly would restrict step duration.

Swing leg actuation is one important aspect closely related to push recovery. Wisse [16] argued that the robot would never fall forward if it moves its swing leg fast enough in front of the support leg. A
recovery step is developed to execute a desired bipedal locomotion for both stationary standing and steady-state walking [15]. Nevertheless, such an infinite swing ability is untrue in the real biped system, because it requires much high driving power to swing its leg that probably beyond the actuation ability.

Human walking is a typical legged locomotion. When given eternal perturbations, humans use active neuromuscular control to stabilize themselves. By exploiting the variability of step position and duration, we can infer how the foot placement of human walking depends on the magnitude of external perturbations. In this paper, we seek to contribute to the following problem: for a biped system recovering balance from external perturbations, how to choose the optimal step length and duration for biped systems if given an arbitrary perturbation.

The reminder of this work is organized as follows. Section II introduces our experimental setup and prototype. In Section III, experimental results and data analysis are demonstrated in detail. Finally, we conclude this paper in Section VI.

Methods

We conducted the balance recovery experiments with a total of 10 males (age = 23.2 ± 1.9 years; height = 1.75 ± 0.06 m; weight = 66.8 ± 10.7 kg). Subjects gave informed consent that is approved by the local Medical Ethical Committee before participation.

We implemented waist-pull perturbations to subjects during standing, who always kept arms crossed in the front of chest, in order to exclude effects of arm swing. Meanwhile, subjects were asked to wear a blinder to exclude vision effects on step decisions. External anterior perturbations are transmitted through one cable mounted on a waist belt worn by the subject. To measure the magnitude of perturbations, a load cell calibrated to record instantaneous cable tension was installed with the cable, close to the subject (see figure 1). Walking motions of subjects were recorded using a six-camera motion capture system (from Motion Analysis), with three markers on each foot including an ankle marker and three markers on the upper pelvic region, close to the center of body mass.

Figure 1. Schematic of the experiment environment. We used a cable mounted on the waist belt to pull the subject, one could restore balance by taking forward steps. The number of steps was not asked before, but we observed that a single step was mostly adopted by subjects, in order to restore balance from various perturbations, as reported in [18]. Pull force was exerted manually and randomly.

When cables were attached to the subject, before giving the actual perturbation, an appropriate force was applied to prevent cable slackening. In the experiment, perturbations were provided along the forward and each perturbation is given after the subject has recovered completely from last
perturbation. In order to reduce the predictability of the upcoming event and obtain unbiased results, the magnitude and period of pull force executed on subjects were provided randomly.

Trajectories of 15 reflective markers attached to the subjects were collected at 120 Hz using a 6-camera motion capture system. Marker paths were low-pass filtered at a cut-off frequency of 6 Hz using a fourth-order, zero-lag Butterworth filter. Timing of foot dynamic phase (i.e., heel strike and toe off) was derived from heel and toe markers’ position. Here, step duration and position after a perturbation are computed according to the position changes of the marker at heel. By integrating force measured by the load cell over time, we obtained the perturbation momentum.

**Results**

Regardless of the magnitude of waist-perturbations, all subjects completed the experiment without difficulty. After the perturbation, all participants were able to recover their balance without falling. Values of the outcome measures obtained are reported in table 1.

Seen from the column of 'Mean step duration' in table 1, a small standard deviation means that step duration maintains virtually constant or fluctuate slightly around the mean step duration, although the magnitude of perturbations varies over a considerable range; all subjects gave evidence of that. The characteristics of step position following various magnitudes of perturbations is captured through linear regression; each subject has a fitting model of step position along with the goodness of fit.

According to the slope of a fit model in the column of 'Fitting step position', there exists a significant positive correlation between step position and the magnitude of perturbations. Concretely, data of foot placement are provided in figure 2, which presents experimental results from subject #1 listed in table 1.

**Table 1. Experimental results with waist-pull perturbations.**

<table>
<thead>
<tr>
<th>Subject</th>
<th>Leg length (m)</th>
<th>Range of perturbations (N-s)</th>
<th>Mean step duration a (s)</th>
<th>Fitting step position b (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.93</td>
<td>20-80</td>
<td>0.3410 (0.0258)</td>
<td>Y=11.04*X+79.26 (0.858)</td>
</tr>
<tr>
<td>2</td>
<td>1.05</td>
<td>20-80</td>
<td>0.3416 (0.0371)</td>
<td>Y=5.62*X+166.90 (0.673)</td>
</tr>
<tr>
<td>3</td>
<td>0.99</td>
<td>25-75</td>
<td>0.2913 (0.0335)</td>
<td>Y=9.92*X+27.40 (0.742)</td>
</tr>
<tr>
<td>4</td>
<td>1.00</td>
<td>15-75</td>
<td>0.3334 (0.0251)</td>
<td>Y=4.87*X+354.40 (0.416)</td>
</tr>
<tr>
<td>5</td>
<td>0.97</td>
<td>20-80</td>
<td>0.3863 (0.0232)</td>
<td>Y=8.04*X+256.90 (0.690)</td>
</tr>
<tr>
<td>6</td>
<td>0.86</td>
<td>20-60</td>
<td>0.2903 (0.0226)</td>
<td>Y=10.43*X+264.40 (0.478)</td>
</tr>
<tr>
<td>7</td>
<td>0.96</td>
<td>20-70</td>
<td>0.3183 (0.0241)</td>
<td>Y=7.73*X+284.40 (0.586)</td>
</tr>
<tr>
<td>8</td>
<td>0.96</td>
<td>20-75</td>
<td>0.3262 (0.0256)</td>
<td>Y=11.91*X+160.70 (0.736)</td>
</tr>
<tr>
<td>9</td>
<td>0.99</td>
<td>20-80</td>
<td>0.3532 (0.0208)</td>
<td>Y=6.88*X+222.70 (0.712)</td>
</tr>
<tr>
<td>10</td>
<td>0.99</td>
<td>30-100</td>
<td>0.2929 (0.0229)</td>
<td>Y=6.26*X+40.41 (0.714)</td>
</tr>
</tbody>
</table>

a Mean step duration: the mean of all step durations under various perturbations; data in brackets are standard deviations.

b Fitting step position: obtained by linear regression, X is perturbation momentum and Y is step position; data in brackets are the goodness of fit.

Curve fitting analysis with Prism 7.0 (from GraphPad) is used to quantitatively evaluate recovery foot placements collected from each subject under various perturbations. Nonlinear regression fits a horizontal line through step duration data in figure 2a, of which the height is the mean of step duration, 0.3410. We plotted 95% prediction bands, visually showing how precisely the horizontal line has been determined. In addition, the line passed the runs test and a normality test (D’Agostino test), indicating that it follows the trend of data well.

Linear regression is used to find the best-fit value of the slope and intercept for step position data in figure 2b. The value R2, 0.858, showed the goodness-of-fit of linear regression was sufficient. Moreover, the P value calculated from F test inferred that the slope was significantly different than zero. Statistical significance was set a P<0.05. Also, 95\% prediction bands gave a visual sense of how well the data define the curve.
Since each individual has a unique set of system constraints and resources available to control posture balance, postural control and falls are context-dependent. Although the regression coefficients of foot placement between subjects are slightly different because of complicated biomechanical factors, it is clear that the common trend of foot placement is a constant step duration and the increasing step position with perturbations. To our knowledge, leg length is one of important factors that causes the difference on foot placement between individuals.

Discussion

This study is designed to investigate foot placement when healthy subjects are exposed to repeated waist-pull perturbations applied during standing. Experimental results show that when stepping for balance from various waist-pull perturbations, one intends to choose an approximately constant step duration, but his/her step position is positively correlated to the magnitude of perturbations.

These current results suggest an effective alternative to predict recovery foot placement of biped systems following unexpected perturbations. Moreover, it is likely that they provide an implication for probes of the fundamental mechanisms underlying human stepping reactions. This is perhaps attributed to the fact that a shorter step duration probably facilitates execution of additional steps, which is much more prevalent in the older adults or in many large perturbations [17, 18]. Conversely, extending step duration may increase the tendency of the COM to fall, because it is difficult for swing foot to catch up with the instantaneous capture point, which increases exponentially with step duration [19]. Therefore, in order to restore balance from larger perturbations, step position taken is likely to increase, but step duration is not sensitive to the increasing magnitude of perturbations. Similarly, Maki et al. [17] have presented that there is a tradeoff between the speed of compensatory step execution and the stability of the resulting for human locomotion; typically, during single-step reactions, the behavior appears to be biased toward achieving stability more than speed.

Although foot placement depends on the combination of biomechanical constraints and cognitive processes, including the individual evaluation of the risk of fall, all subjects have contributed a common trend of results. It suggests that when stepping to recover balance, biped systems tend to choose a regular step duration, while its step position linearly increases with regard to the variation of perturbations. These results are potentially applied to the control of biped walking, providing the prior foot placement for balance recovery under perturbations. Also, these results could help to design effective fall-prevention programs to target the specific needs of enrolled subjects.
Acknowledgment

This research was supported in part by National Natural Science Foundation of China under Grant 61533004, Grant U1613206, and in part by Beijing Municipal Science & Technology Commission (No Z161100000516033).

References


