Toward general capture point-based analysis on standing, walk and slip: the connection between robotic motions to human behaviors

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Summary

Stepping is one of the main strategies for human to recover due to unexpected external. There have been studies related to stepping for balance recovery in both robotics and biomechanics. However, few studies have investigated its relationship between different tasks (e.g. step initiation, walking, and slipping) or different walking types (e.g. passive or active walking, walking with flat foot or rolling foot), which motivated us to use Capture Point (CP) as a starting point. CP is the stepping location which can make a complete stop for a legged system. In this study, we present analyses based on CP to investigate the stepping estimation among different walking tasks and walking types in two ways: 1) comparisons between a simplified robotic model and human for step initiation from standing, and 2) comparisons among several bipedal walking with different controls, human normal walking and walking with a slip. The results showed that CP-based analyses could provide reasonable predictions for step initiation for simplified model and human, and for human walking and walking with a mild slip, whereas further considerations of effects from upper body motion, stepping impact, and dynamics in double support need to be considered for better stepping location estimation for other walking types.

Introduction

Human's ability to recover from unexpected slip, trip and fall seems to be very robust. To design the robust controllers for bipedal robots and lower-limb prostheses, therefore, understanding the stability measures that connect between robotics and biomechanics is crucial. For this purpose, important characteristics of an ideal stability measure are expected to quantify stability across different walking types of robots, humans, or humans with locomotor pathologies. In addition, it should further provide connections between different tasks (e.g., normal walking, push recovery with single or multiple steps, slip recovery). Among several attempts to measure the stability of a legged system [1], Capture Point (CP) [2] can provide desirable descriptions for both stability and control. As mentioned above, CP is the stepping location for a legged system to make a complete stop with one step. With a simplified Linear Inverted Pendulum (LIP) model, *Instantaneous* CP (ICP), or 1-step CP, could be derived as shown [2]:

$$x_{ICP} = x_c + \dot{x}_c / \omega \qquad (1)$$

where x_c is the COM position in x direction (i.e., sagittal plane), x_{ICP} is the capture point at current time step. $\omega = \sqrt{z_0 / g}$, where z_0 is the COM height and g is the gravity constant. Capture point has also been extended to "*N*-step CP" (i.e. stop after *N* steps) and "∞-step CP" (i.e. normal walking) [2]. Although the properties of CP provide a more general description on walking balance and control [1-2], the validity of analyses based on CP still need more clarifications for studying stepping strategies among various walkers and tasks, which drives us to investigate CP-based analyses described in the next section. In the result section, comparisons between various tasks and walking types are presented.

Methods

We present two main parts for the CP-based analyses on standing, walking and slipping. The first part is the validation of CP-based analysis for two stationary tasks (one is single step initiation from the release at specific inclined angles [3], and the other is single step initiation due to maximum constant forces [4]) :

- Compare the estimated *1*-step CP using Eq. (13) and (22) in [2] to the results of human foot placement presented in the literature [3-5].

Second, for the non-stationary tasks such as walking and walking with a slip, we define an estimated ICP (EICP) and make comparisons as follows:

- To avoid using predetermined parameters such as step length and step time required for calculating ∞-step CP (Eq. (17b) in [2]), the EICP is defined as $x_{EICP} = x_c + \dot{x}_{c,Desired} / \omega$.

- Compare the errors of *1*-step CP (Eq. (1)), ∞-step CP, EICP with respect to actual stepping locations of a compass gait (CG) robot (2 links), a kneed gait robot (5 links) with underactuated (KGUA) or actuated (KGFA) ankle joints with human-inspired control, one 7-link robot with ZMP-based flat-footed walking, normal human gait, and human gait with mild and severe slip (i.e. peak heel slip velocity > 1.44 m/s).

Results

The step location estimations for stationary tasks are shown in Fig. 1 and 2. Except the one with 27.5° angle in Fig. 1, ICP gave reasonable stepping predictions.

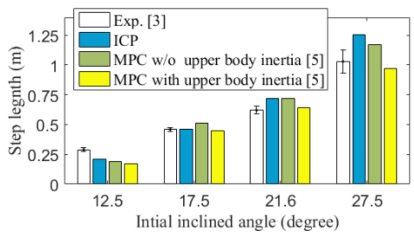

Fig. 1. Step location comparison between ICP and results in [3,5]

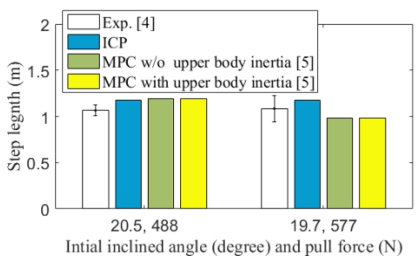

Fig. 2. Step location comparison between ICP and results in [4,5]

For the non-stationary tasks, the main specifications of walkers are listed in TABLE I, and the normalized step location estimation errors are listed in TABLE II.

TABLE I. Parameters of walkers (values in parentheses indicate the standard deviation)

	CG	KGUA	KGFA	ZMP	Human
Height (m)	0.90	1.0	1.0	1.50	1.73 (0.08)
Weight (Kg)	50	70	70	28.18	69.05 (12.02)
Speed (m/s)	0.6	1.36	1.18	0.07	1.39 (0.23)

In TABLE II, all estimated step lengths of CG and KGUA were longer than the actual ones. On the contrary, the estimated step lengths of KGFA and ZMP were shorter than the actual step lengths. The estimated CPs for normal human walking and human walking with a mild slip were more accurate than other walkers. However, the estimated CPs did not seem to explain the human walking with a sever slip. Even the ∞-step CP failed to give an reasonable estimation for severe slip possibly due to the much smaller stepping time.

TABLE II. Etimation error of step location (normalized by step length) for different walkers and difference tasks. The values in the parentheses indicate the standard deviation.

	CG	KGUA	KGFA	ZMP	Human (walk)	Human (mild slip)	Human (severe slip)
1-step CP	0.327 (0)	0.603 (0)	-0.269 (0)	-0.225 (0)	0.06 (0.033)	0.074 (0.038)	0.379 (0.102)
∞-step CP	0.133 (0)	0.417 (0)	-0.154 (0)	-0.225 (0)	0.024 (0.028)	-0.174 (0.066)	>1.00
EICP	0.048 (0)	0.473 (0)	-0.031 (0)	-0.182 (0)	0.023 (0.029)	0.078 (0.041)	0.341 (0.057)

Discussion

For the stationary tasks, the larger stepping estimation errors of ICP for 27.5° angle (Fig. 1) seemed to be caused since the CP was calculated without considering the upper body inertia during recovery. On the other hand, the reasons for discrepancies of estimation in TABLE II seemed to be more diverse. For the robots without ankle-actuation, the lack of combining impact in calculating CPs may have caused the error. For robots with fully-actuated ankles, double support phase may have become a more dominant phase to propel the body (especially for ZMP walking), resulting in significantly different ways of stepping compared to the LIP model's free sway. For the step location estimations of human walking with a severe slip, the swinging foot tended to land (or scuff) prematurely to make the legged system back to the double support phase until the slip velocity decreases, thus the behavior was quite different from stepping. In conclusion, the stepping location estimations using *1*-step CP, ∞-step CP and EICP could provide reasonable predictions for human normal walking and human walking with mild slip, whereas for severe slips, CP-based method needs to be improved for better stepping location estimations.

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