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

HUMAN REHABILITATION (HUR) Group

Kenneth Yi-wen Chao and Pilwon Hur, Ph.D.

http://hurgroup.net

kchao@tamu.edu, pilwonhur@tamu.edu

Summary

- Stepping is one of the main strategies for human to recover due to unexpected external disturbances. 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).
- In this study, we use Capture Point (CP) as a starting point and present CP-based analyses to investigate the stepping estimation among different walking tasks and walking types for both stationary tasks (one-step recovery from standing) and non-stationary tasks (walking or walking with slip).

Capture Point, Instantaneous Capture Point, ∞-step Capture Point and Estimated Capture Point

- CP is the step location for a legged system to make a complete stop with one step, which can provide desirable descriptions for both stability and control.
- With a simplified Linear Inverted Pendulum (LIP) model, Instantaneous CP (ICP) can be derived as:

$$x_{ic} = x_c + \frac{\dot{x}_c}{\omega} \qquad \begin{array}{l} x_c: \text{ COM position} \\ x_{ic}: \text{ ICP} \end{array}$$

- When the legged system make a step on the ICP, the ICP becomes a Capture Point (1-step CP).
- Capture point has also been extended to "N-step CP" (i.e. stop after N steps) and "∞-step CP" (i.e. for nor mal walking), which can be calculated as follows [2]:

$$d_\infty = l_{max}\frac{e^{-\Delta t_s}}{1-e^{\Delta t_s}} \qquad \begin{array}{l} l_{max}: \text{ Max reachable range} \\ t_s: \text{ Stepping time} \end{array}$$

- To avoid using predetermined parameters such as st ep length and step time required for ∞-step CP , Estimated ICP (EICP) is another quantity which we use the same equation as ICP but replace the center of mass (COM) velocity to the average one.

Comparisons for Stationary Tasks

- For stationary tasks, we compare the experimental data with estimated 1-step CP using ICP, and the simulation with model predictive control (MPC).
- There are two tasks for comparisons
  a) Standing subjects released from specific inclined angles
  b) Standing subjects resisting applied forces (gradually increasing) until making a step

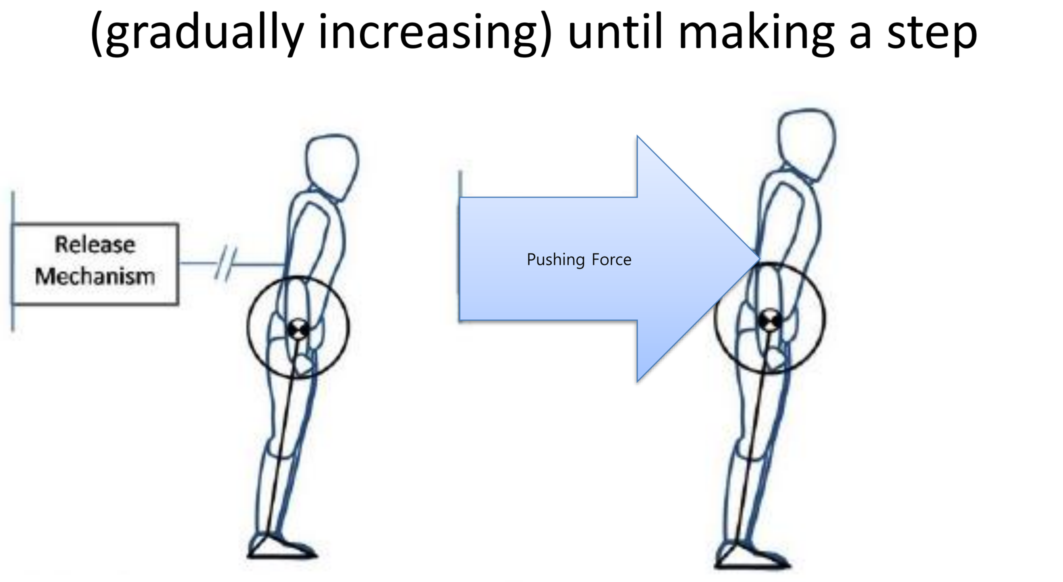

Fig. 2 Schematic diagram for stationary Task 1 (left) and Task 2 (right)

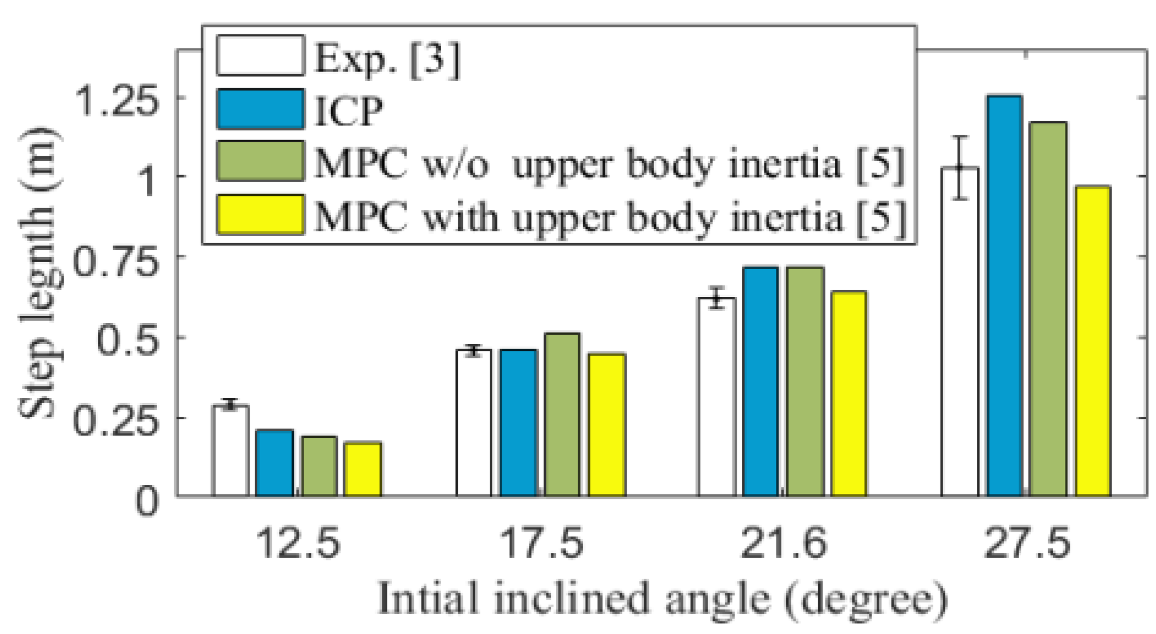

Fig. 2 Step location comparison between the experiment[3], ICP and MPC[5] for Task 1.

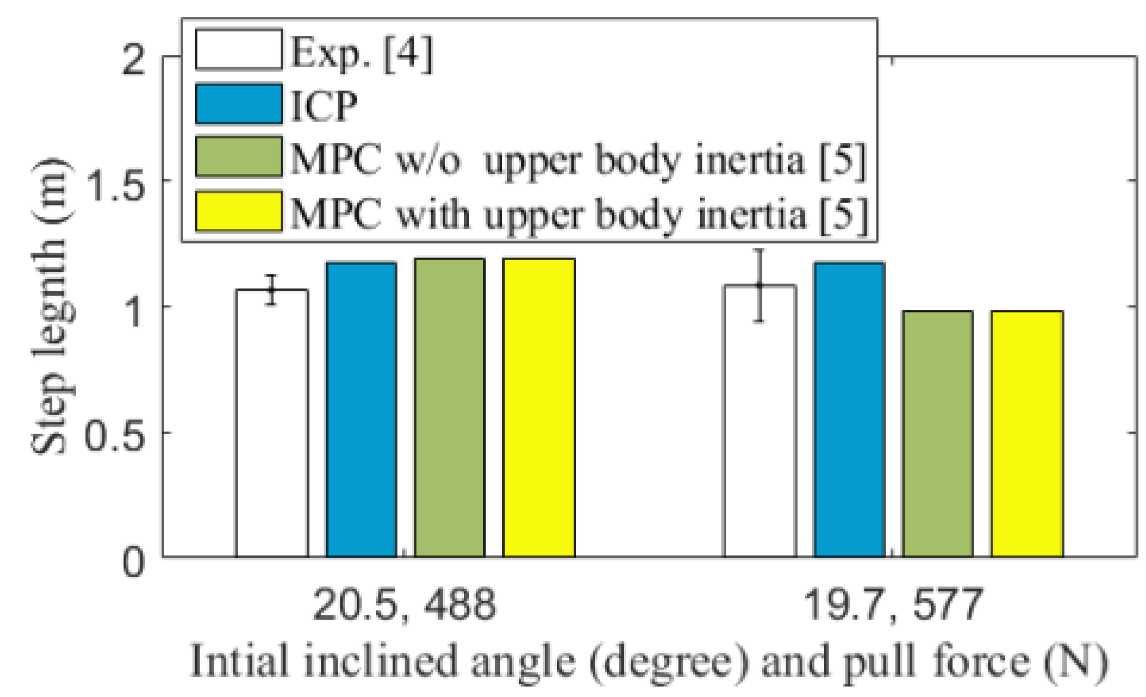

Fig. 3 Step location comparison between experiment[3] ICP and MPC[5] for Task 2.

- From Fig.2 and Fig.3, ICP gave reasonable stepping predictions for most of cases. The larger stepping estimation errors of ICP for 27.5° angle (Fig. 2) happened because the CP was calculated without considering the upper body inertia during recovery.

Comparisons for Non-stationary Tasks

- For non-stationary tasks, we compare the errors of 1-step CP, ∞-step CP, EICP with respect to actual stepping locations (TABLE II.) of a compass gait (CG) robot (2 links), a kneed gait robot (5 links) with under-actuated (KGUA) or actuated (KGFA) ankle joints with human-inspired control, one 7-link robot with ZMP-based flat-footed walking (TABLE I.), normal human gait, and human gait with mild and severe slip (threshold: peak heel slip velocity > 1.44 m/s).

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)

- For under-actuated walking CG and KGUA, the estimated step lengths was (much) larger than the simulation one, which might be because the current method did not consider the power dissipation due to impact.
- For full-actuated walking KGFA and ZMP, the real step length was (much) less than the simulation one.
  - The activated ankle regulated the COM velocity dominantly (usually reducing or limit the velocity during walking), which made the walker not really behave like a free-swaying IVP.
  - A certain portion of COM moving was achieved in double support rather than in single support (for the ZMP-based walker).
- Surprisingly, ICP or EICP gave a relatively better esti- mation for both walk and walking with mild slip.
  - May imply the human actually behave neither pure-under-actuated or pure-full-actuated.
  - Humans tend to reduce the impact for landing, they also tend to utilize the free-sway dynamics when walking in a safe region.
  - Human use similar control strategy as walking for mild slip.
- For the severe slip, ∞-step CP failed, and the esti- mation error for both ICP and EICP were also large.
  - The swing leg tended to make a step immediately. (Usually still behind the front support foot.)
  - EICP and ICP might not provide good estimation because it is less clear of how ICP works in the double support phase.

Conclusions

- Stepping location estimations using CP-based method can provide reasonable predictions for one-step recovery from standing, human normal walking and human walking with mild slip.
- For severe slips, CP-based method needs to be improved for better stepping location estimations.
- The upper body motion, the effects of impact and the COM motion in double support phase need to be considered for further development of foot placement estimation.

References

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[4] K. E. Moglo et al., *In ISB XXth Congress*, (2005).
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TABLE II. Estimation 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)