The Effect of Vertical Motions on the Balance Recovery Prediction for Standing Humans through Linear MPC

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***Abstract*— This paper presents a contribution that is part of a larger project, consisting of developing a human-like gait and balance recovery simulator based on an linear model predictive controller. This paper specifically focuses on the influence of restricting or not the vertical dynamics of the whole body center of mass on the biped's balance recovery capacity.**

I. INTRODUCTION

Modeling the balance recovery of humans allows both a better understanding of the balance recovery mechanisms - that could be reinvested to improve the stability of biped robots - and the identification of the situations at higher risk of fall (e.g. perturbations such as an emergency breaking in public transports, degradation of the physiological capacities due to ageing or disease, etc.). Previous studies previously conducted in our laboratory have demonstrated that a linear model predictive control is a very promising techniques, allowing to reproduce human-like behavior with a numerically efficient and robust controller relying on a meaningful (i.e. interpretable) set of parameters [1], [2], [3]. However, the controllers used in these studies relied on a linearized inverted pendulum internal model, i.e. considered that the whole body center of mass (WBCoM) remained at a constant altitude. Thanks to this linearization of the system's dynamics, the optimization problem could be solved using efficient and robust QP solvers. However, regulating the vertical dynamics of the WBCoM has an impact on its horizontal dynamics (see Equation (1) below) and could thus represent a balance recovery mechanism: to the extreme case (free falling) the WBCoM is not anymore accelerating away from the ZMP (CoP). One can notice that, this mechanisms received only limited attention. To our best knowledge its effect on balance recovery was not quantified in human experiments. Interestingly, a recent study ([4]) proposed an approach to free the constraint on the vertical dynamics of the WBCoM while keeping the optimization problem quadratic. This approach was demonstrated on walking on flat and uneven terrain. In this study, we would like to investigate if this approach could be used for balance recovery following large perturbation, and, more specifically, if it improves the balance recovery capacities of human-like bipeds.

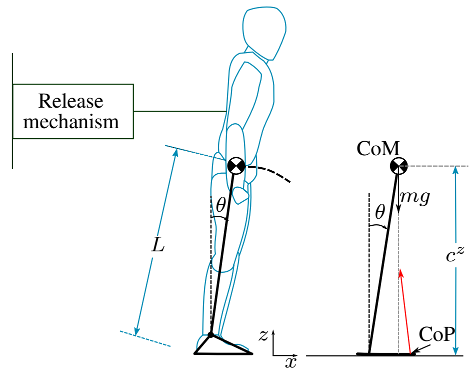

Fig. 1: The representation of the human body.

II. METHOD

The dynamic model of the human is found using the Newton-Euler equations and considering zero angular momentum, the motion of the CoM c of the human can be related to the CoP p of the contact forces with the ground (see Figure 1 in sagittal plane) in the following way [5]:

$$p^{x,y} = c^{x,y} - \zeta \ddot{c}^{x,y} \tag{1}$$

with

$$\zeta = \frac{c^z - p^z}{\ddot{c}^z + g}, \tag{2}$$

where g is the vertical acceleration due to gravity, ^{x} and ^{y} refer to horizontal coordinates while ^{z} refers to the vertical coordinate. The variation of ζ can be reasonably bounded by $\underline{\zeta}$ and $\overline{\zeta}$ during stepping motions [5]. In this case, (1) yields

$$p^{x,y} \in [c^{x,y} - \overline{\zeta}\ddot{c}^{x,y}, c^{x,y} - \underline{\zeta}\ddot{c}^{x,y}] \tag{3}$$

The controller was proposed by Pajon *et al.* [4], to generate 3D walking motions. In our simulation case, we focus on the balance recovery reaction in sagittal plane i.e. x-z plane as shown in Figure 1. By ignoring y axis, we can rewrite the equation (3) as

$$p^{x} \in [c^{x} - \overline{\zeta}\ddot{c}^{x}, c^{x} - \underline{\zeta}\ddot{c}^{x}] \tag{4}$$

which is equivalent to

$$l_{min}(\underline{\zeta}\ddot{c}^x) \leqslant c^x - p^x \leqslant l^{MAX}(\overline{\zeta}\ddot{c}^x) \tag{5}$$

where $(l^{MAX} - l_{min})$ is the maximum allowed displacement of $(c^x - p^x)$ (see Figure 2), and is bounded by a new interval $(p^{MAX} - p_{min})$ specified by the base of support (BoS) and the position of CoM.

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Note that, too large windows $\{\underline{\zeta}, \overline{\zeta}\}$ lead to infeasible solutions. On the opposite, too small windows will stronlgy constrain the vertical dynamics of the WBCoM (at the extreme case, $\underline{\zeta} = \overline{\zeta}$ lead to fully constrained dynamics, with for example the WBCoM constrained at a constant altitude if $\ddot{c}_0^z = \dot{c}_0^z = 0$). Thus, this window should be carefully adjusted, in particular for large CoM dynamics $\ddot{c}^x$.

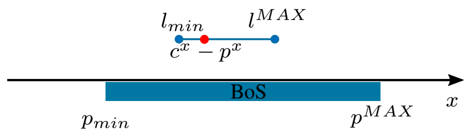

Fig. 2: The boundaries of the CoP.

In this study we investigated the effect of varying the size of this windows on the single-step balance recovery capacity in tether-release (release in an unstable inclined state). For different recovery step duration and step time and $(\underline{\zeta}, \overline{\zeta})$ interval, we iteratively look for the maximal release angle for which the model could still recover its balance in a single step. Note that the initial condition had to be carefully adjusted for each release angle θ: considering that $\ddot{c}_0^z = 0$, equation (2) yield to $\zeta_0 = L.\cos(\theta)/g$ and (1) to $\ddot{c}_0^x = g\tan(\theta)$. Model parameters were derived from previous studies where a similar model - but using a linear inverted pendulum - was used to reproduce human balance recovery in similar conditions.

III. RESULTS

In this section, a briefly discuss the results of the one-step balance recovery strategy in the sagittal plane using linear MPC. Figure 3 shows the maximum release angle as a function of different step time and different value of the $(\underline{\zeta}, \overline{\zeta})$ interval. Overall these results match those obtained in human experiments, where the maximal release angle is about 23° [6] with an optimal step duration of about 440 ms. More interestingly, we observe that varying the size of the $(\underline{\zeta}, \overline{\zeta})$ has almost no effect on the maximal release angle, and that results were similar to those obtained with a LIPM. It appears that, for this largely perturbed condition, the two effects of increasing the $(\underline{\zeta}, \overline{\zeta})$ interval (i.e. a more constrained displacement of the CoP) and decreasing it (i.e. a more constrained vertical dynamics of the WBCoM) compensate each other. In walking motions, Serra $et\ al.$ [7] have that a large range leads to much more conservative constraints, while choosing a small range leads to better results.

IV. CONCLUSION AND DISCUSSION

In this paper, we investigate the usefulness of an approach that allows simulating bipedal walking and balance recovery with a linear MPC scheme with a non-constraint vertical dynamics of the WBCoM. This approach proved to be efficient in slightly perturbed situation [4]. However, in this study we considered situation with high dynamics due to large balance perturbations. In such situations, the proposed approach provide similar results to those obtained with a classical LIPM. One may still wonder if solving the problem using a non-linear approach would change this results. If we cannot answer from this study, we can still observe that: 1) Results obtained match quiet closely those observed in humans; 2) Adjusting the vertical dynamics of the WBCoM has not been described as a strategy to restore balance in biomechanics literature. As such it seems that the proposed approach from [4] is relevant for both slightly and largely perturbed situations such as walking and extreme balance recovery.

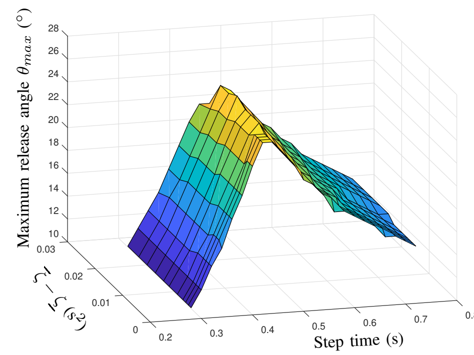

Fig. 3: Maximun release angle (θ^{max}) vs step time and the interval $(\underline{\zeta}, \overline{\zeta})$.

Regardless of the case study in this paper, the proposed approach offers new additional features such as a three-dimensional (3d) balance recovery, adaptable step placement, complete kinematic and dynamic feasibility guarantees, and it can used for different human balance tasks. At present the proposed MPC scheme can handle also different recovery strategies in parallel, including the ankle, hip, and stepping strategies include the use of variable step duration. Future work will be directed towards to improve the model to simulate a strong perturbation and then extending it to include multi-contact and evaluating the method on different tasks using a different external physical model.

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