Optimising balance margin in lower limb exoskeleton to assist user-driven gait stability

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***Abstract*— When exoskeletons are driven in open loop with predetermined trajectories, the onus is placed on the user to maintain balance through their crutches. This work uses simulation of a human-exoskeleton model to explore the idea that such trajectories could be optimised to give the user the 'best chance' to maintain their balance in the presence of perturbations. The method evaluates a reward function under different gait trajectories and initial poses. It is concluded that such an optimisation method could increase the set of perturbations which a user can counter without adding significant complexity or expense to the exoskeleton.**

I. INTRODUCTION

The present work investigated the idea of using a step-specific optimisation of the gait trajectory to give the user the 'best chance' to deal with perturbations. To do this, a reward function related to the balance margin near (nominal) heel strike was defined. The balance margin is correlated with the size of perturbation that can successfully be countered by the user, and the time near heel strike is when perturbations due to uneven ground are likely to occur. Using a model-based simulation, the reward function was evaluated across different crutch placements (accounting for different crutch placements at each step) and different gait trajectories. The results indicate that no single trajectory is optimal across all crutch positions, suggesting that a user could maintain balance against a larger set of perturbations, if the gait trajectory is optimised for this.

II. MATERIALS AND METHOD

This study aimed to evaluate whether changes in gait trajectory affect the ability of an exoskeleton user to maintain balance, through model-based simulations of a balance-related reward function across different parameterised gait trajectories.

A. Human-Exoskeleton Model

The human-exoskeleton system was modelled as ten rigid links and ten degrees of freedom (Fig. 1a). The modelled lower-limb exoskeleton has three actuated degrees of freedom on each leg — hip and knee flexion/extension and ankle dorsi-/plantar flexion. The inertial parameters of the body segments were based on average values [1], with additional exoskeleton masses. The pose of the system is thus described by $\mathbf{x} = [\mathbf{q}, \mathbf{x}_{c,L}, \mathbf{x}_{c,R}] \in \mathbb{R}^{10}$, where $\mathbf{q} \in \mathbb{R}^6$ are the joint angles of the ankles, knees and hips, and $\mathbf{x}_{c,L}, \mathbf{x}_{c,R} \in \mathbb{R}^2$ are the positions of the left and right crutch in the horizontal plane.

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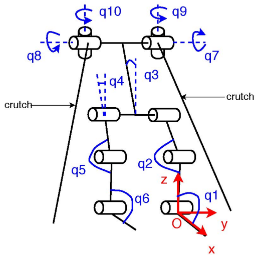


(a) Kinematic model

(b) Real system

Fig. 1: The human-exoskeleton system

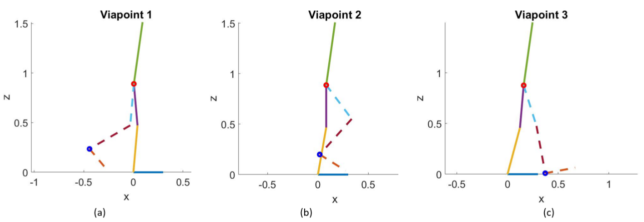


Fig. 2: Via points of joint trajectory (dashed line representing the swing leg): (a) heel lift at $t_1 = 0.4t_f$ (b) maximum toe clearance at $t_2 = 0.6t_f$ (c) heel strike at $t_3 = 0.9t_f$

B. Gait Parameterisation

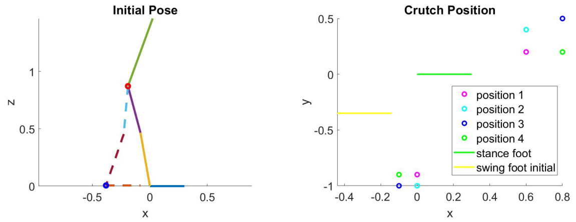
For purposes of illustration, the joint trajectory for each step is parameterised by step length only. The hip and ankle positions ($\mathbf{x}_{hip}, \mathbf{x}_{ankle}$) are specified at three via points (see Fig. 2). Trajectories are then constructed as a series of polynomials, ensuring continuity in position, velocity and acceleration for whole gait. Inverse kinematics are then used to compute the joint trajectories $\mathbf{q}(t)$.

C. Reward Function

The reward function is defined as a measure of how large a perturbation can be rejected by the user particularly near heel strike, when perturbations related to uneven ground are most likely to be encountered. For a given joint trajectory $\mathbf{q}(t), t \in [0, t_f]$ (where t_f is step duration), this is defined as:

$$J(\mathbf{q}(t), t, t_f) = \int_{0.8t_f}^{t_f} d(\mathbf{q}(\tau), \tau) d\tau$$

where $d(\mathbf{q}(\tau), \tau)$ is the distance between the location of the Zero Moment Point (ZMP) [2] and the nearest edge of the support polygon, on the assumption that the ZMP remains within the support polygon (*i.e.* $d(\mathbf{q}(\tau), \tau) > 0$). This reward function considers the margin of stability in the last 20% of the gait period, assuming that nominal heel strike occurs at $0.9t_f$. A larger value indicates that a larger perturbation



(a) The initial pose (b) Crutch positions

Fig. 3: Initial Conditions

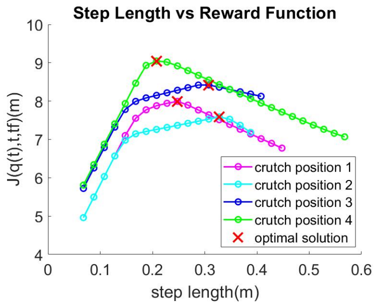


Fig. 4: The resulting evaluation of the reward function($t_f = 1.5s$).

is required to turn over the human exoskeleton system [3], translating to the user having a 'better chance' of maintaining balance when a perturbation is encountered.

D. Simulation and Evaluation

An illustrative example is presented representing situations in which crutches position must be varied (for example, due to obstacles on the ground). Specifically, the exoskeleton's initial posture is defined ($\mathbf{q}(t_0)$), but crutch positions are varied ($\mathbf{x}_{c,L,i}, \mathbf{x}_{c,R,i}$) (see Fig. 3). The positions of crutches were chosen to compare different sizes and shapes the of support polygon as follows:

$$\begin{aligned}
&\mathbf{q}(t_0) = [100^\circ, 175^\circ, 20^\circ, -5^\circ, 166^\circ, 71^\circ]^T \\
&\mathbf{x}_{c,L,1} = [0.6, 0.2]^T, \qquad \mathbf{x}_{c,R,1} = [0, -0.9]^T \\
&\mathbf{x}_{c,L,2} = [0.6, 0.4]^T, \qquad \mathbf{x}_{c,R,2} = [0, -1]^T \\
&\mathbf{x}_{c,L,3} = [0.8, 0.2]^T, \qquad \mathbf{x}_{c,R,3} = [-0.1, -1]^T \\
&\mathbf{x}_{c,L,4} = [0.8, 0.2]^T, \qquad \mathbf{x}_{c,R,4} = [-0.1, -0.9]^T
\end{aligned}$$

Trajectories were generated using the parameterisation defined in section II-B, with step lengths between 0 and $0.6m$, and trajectories resulting in constraint violation (ZMP outside the support polygon) were removed. The reward function was calculated for the remainder of the trajectories.

III. Results

Fig. 4 illustrates the evaluation of the reward $J(\mathbf{q}(t), t, t_f)$ for various step lengths.

IV. Discussion

The results show that under different crutch positions, the reward function is maximised by different step lengths. This suggests that an optimisation-based gait trajectory generation method can be used to give the user the 'best chance' of maintaining balance. For example, if the user places their crutches in crutch position 4, and the optimal step length from crutch position 1 is used to generate the gait trajectory, a smaller set of perturbations can be accounted for by the user (compared to if the optimal for position 4 is used).

Whilst the example presented here assumes that the height of the crutch position does not vary, this would be an obvious extension which could result in a better estimate of balance margin when steps are encountered. It is also noted that many other gait parameterisations are possible, such as varied toe clearance, final step height, and step duration, which could result in even larger differences between optimal and non-optimal solutions. However, implementation on a real system will require an optimisation to be run online, which may also present a challenge. This may require simplification of the problem statement, or pre-calculation of the solutions.

V. Conclusion

This work investigates the utility of a trajectory generation method which optimises an 'end of step' balance metric, corresponding to the idea that this gives the user the 'best chance' of maintaining balance. The results illustrate that the optimal step length varies with different crutch positions, indicating the potential benefits of using this approach.

References

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