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A gain-scheduling approach to model human simultaneous visual tracking and balancing.

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Abstract— **In this study, we endeavor to better understand the human motor control system in order to help transposing some of its features onto humanoid robots. The postural coordination task investigated is related to an experimental paradigm that consists in visual target tracking task while balancing. We want to test whether the human biomechanical responses, namely phase / antiphase coordination mode transition, as exhibited during the actual experiments can be modeled by a linearized double inverted pendulum and parallel independent PD feedback control loops. Remarkably, these loops implement joint space control using cartesian task space variables. Furthermore, we want to see how the feedback control gains given by an optimization procedure scale w.r.t frequency or target motion magnitude. A closed-loop synthesis is developed that consists in minimizing a minimum torque criterion under both balance and task constraints. We show that the optimal feedback control gains obtained yield model responses consistent with the literature. In a second part, we implement a gain-scheduling approach where control gains values are predicted via interpolation. Finally, our approach implements a controller capable of achieving the task even when the frequency of the target motion varies over time.**

I. INTRODUCTION

Wouldn't be easier to have humanoid robots that behave in a human way when performing a visual tracking task in balanced stance? One way to help address this issue is to better understand the human motor control system in order to transpose some of its features onto humanoid robots.

In human movement science, the experimental paradigm consisting in tracking a visual moving target in balanced stance has been very often studied [1], [2], [3], [4], [5]. Considering a visual tracking task in the sagittal plane, [2] examined full body joint coordination. The experiment implied having participants moving back and forth in the sagittal plane in order to track a virtual target. This experimental paradigm emphasized key properties for the human postural control system, such as phase transition, multistability, critical fluctuations, hysteresis, and critical slowing down. Two coordination modes that depended on the target's motion frequency were presented: An in-phase mode for low frequencies, where the ankle and the hip joints are moving simultaneously in the same direction, and an anti-phase mode for high frequencies, where the two joints are oscillating simultaneously in opposite directions. An offline optimization of a dynamical model predictions is proposed in [4] in order to analyze the experimental findings reported in [2]. The joint angles trajectories were approximated with a Fourier series, then an integral torque change criterion was minimized under a balance constraint. The results shows that the optimization process predicts changes between in-phase and anti-phase modes of postural coordination. For the same experimental paradigm, [5] proposed a non-linear closed-loop optimal model that predicted changes between in-phase and anti-phase postural coordination. In the latter study, the control torque related to the tracking task was obtained by using a pseudo-inverse Jacobian matrix and an adaptive saturation of ankle torque was used to keep balance constraint satisfied. The two papers [4] and [5] used a similar constraint in the optimization algorithm that ensured balance: The center of pressure(CoP) had to remain within the base of support (BoS)[6]. Nevertheless, it is not clear which integral criterion is actually minimized by the closed loop scheme proposed in [5] .

The idea of using feedback loop to model the human motor control system is not new. In [7], human postural responses to platform perturbations during standing are described in terms of a linear dynamical model with Proportional-Derivative (PD) feedback loops which control gains are scaled and selected by the central nervous system (CNS). The appropriate values for the gains are obtained via model-data fitting using actual experimental data. Moreover, [8] showed that a PD feedback loop with scaled gains can accurately model the postural response to a forward push recovery, the scaling depending on perturbation type.

In this paper, we want to investigate whether the human biomechanical model, represented by a linearized double inverted pendulum, in a closed loop optimal control, with gains synthesized and scaled using an integral criterion can efficiently model the visual tracking task experimental paradigm described above. More precisely, we will consider two PD feedback loops: a short loop that will address the balancing issue, and a long loop that will address the visual tracking task. For given target motion frequency and magnitude, we will compute optimal gains, and then will analyze how they scale, hence the gain-scheduling.

Gain-scheduling in our experimental paradigm is not new in humanoid robotics literature. [9] presents a full-state parametric controllers for humanoid robots standing balance in response to impulsive and constant pushes, where gain-scheduling were explored. In [10], two postural strategies are observed when the whole body reacts to an external perturbation: ankle and hip strategies. In ankle strategy the

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oscillation of the body is around the ankle joint, and in the hip strategy the upper body leans backward and forward. This result inspired the development of balance controllers that helped humanoids recover from a disturbances while still maintaining an upright posture [11]. The latter reference also presented a model tracking control algorithm to make humanoids robots behave in a similar way to humans. Balance issue was also studied on humanoids for different purposes, for example a hydraulic humanoid was used in [12] to have a practical exploration of the effects of modeling error and unknown forces on state estimation for dynamic humanoids balance, while in [13] a feedback controller for the joint position was designed where a switching was performed between gains according to the Zero moment point (ZMP) location in order to maintain balance. [14] developed a standing balance controller that handles unexpected pushes. The linear quadratic regulator was compared to an optimal controller, using the same optimization criterion, to demonstrate the performance of their proposed method. A control framework for humanoid robots was presented in [15]; it includes both a balance and a tracking controller that use all joints simultaneously to track motion capture data while maintaining balance. After studying in more details the experimental paradigm proposed by [2] , [16] implemented the obtained coordination modes on the HOAP3 and HRP2 humanoid robots. They show that the in-phase mode corresponds to the minimum energy mode, and that only the anti-phase mode was able to maintain balance for high frequencies.

In this study the biomechanical model selected is a linear double inverted pendulum type, controlled by two PD feedback loops, one to maintain balance while standing and another to achieve the visual tracking task. The feedback control gains, necessary to accomplish our experimental paradigm are scaled and selected frequency by frequency for different target magnitudes, by minimizing a torque criterion under both environmental and intentional constraints. Furthermore, the optimal gain values obtained from the synthesis are used in a gain scheduling trial. This trial consists in applying a signal with different frequencies, some of which were not addressed in the synthesis task, that will increase in time at a given target motion amplitude.

The paper is organized as follows. Section II introduces the closed-loop feedback control modeling for the biomechanical model and the environmental constraint. Section III develops our gain synthesis approach, then the gain-scheduling technique is proposed in Section IV. Finally, concluding remarks are drawn in Section V.

II. MODELING POSTURAL COORDINATION

A. Biomechanical model

During the visual head tracking task, the biomechanical model is represented as a two-link inverted pendulum (DIP) (Fig.1(a)). Two feedback controllers are used to generate corrective joint torques. The two rigid links represent the head, arms, torso, both legs and both feet. The head, arms and torso were represented by a link according to the minimal motion observed between these segments [17]. The interested control inputs are the torques acting on the ankle and hip. The outputs of interest are the angular position of each body segment: legs and torso. The nonlinear motion equations have the following form:

$$M(q,\dot{q})\ddot{q}+C(q)\dot{q}+G(q)=\tau \tag{1}$$

Where q, $\dot{q}$, $\ddot{q}$ are the vector of joint angles, the angular velocities and accelerations, τ is the vector of joint torques, the inertia matrix M, the Coriolis matrices C and the gravity vector G of the double inverted pendulum are composed of the mass m, length of the segments l, k, center of mass position kl, gravity constant g.

The nonlinear motion equations were linearized with respect to the horizontal axis [8]:

$$M\ddot{q}-Gq=\tau \tag{2}$$

where M is the inertial matrix and G is the gravity matrix. τ is the joint torque where muscles act as actuators. As shown in [18] the muscles act like a first order low-pass filter (3).

$$H_{muscle}(s)=\frac{1}{s+1} \tag{3}$$

B. Balance maintenance - CoP

The maintenance of balance during a tracking task in the sagittal plane depends on the position of the CoP in the BoS

Equilibrium exists when the sum of total moment is equal to zero, hence

$$F_{ver}X_{CoP}+F_{hor}d-\tau_1-m_0k_0g=0 \tag{4}$$

where F_{ver} and F_{hor} represent the vertical and horizontal ground reaction force components. These two components are calculated using Euler's equations, and as showed in [19] they can be related to the change of the respective horizontal and vertical linear momenta of the whole system at each time t. The position of the CoP (Fig.1(b)) on the x-axis is given by

$$X_{CoP}=\frac{\tau_1+m_0k_0g-F_{hor}d}{F_{ver}} \tag{5}$$

C. Closed-loop modeling

To perform the head tracking task, in a closed loop situation, a corrective joint torque needs to be applied to the ankle and hip joints. We propose two PD controllers, one to maintain balance while doing the task and another to achieve the target tracking task while keeping balance. (Fig.1(c)). The state space vector x of the joint kinematics is defined as

$$x=[q_1 \quad q_2 \quad \dot{q}_1 \quad \dot{q}_2]^T$$

where q_1, q_2 are the ankle and hip angular positions, while $\dot{q}_1$, $\dot{q}_2$ are the ankle and hip angular velocities, respectively.

Feedback control input u represented by the ankle and hip joint torques $\tau=[\tau_1 \quad \tau_2]^T$, is generated by the full-state feedback, that has the following form:

$$\tau=\begin{pmatrix} k_{p11} & k_{p12} & k_{d11} & k_{d12} \\ k_{p21} & k_{p22} & k_{d21} & k_{d22} \end{pmatrix}\Delta x + \begin{pmatrix} k_{p1} & k_{d1} \\ k_{p2} & k_{d2} \end{pmatrix}\begin{pmatrix} \Delta h \\ \Delta\dot{h} \end{pmatrix} \tag{6}$$

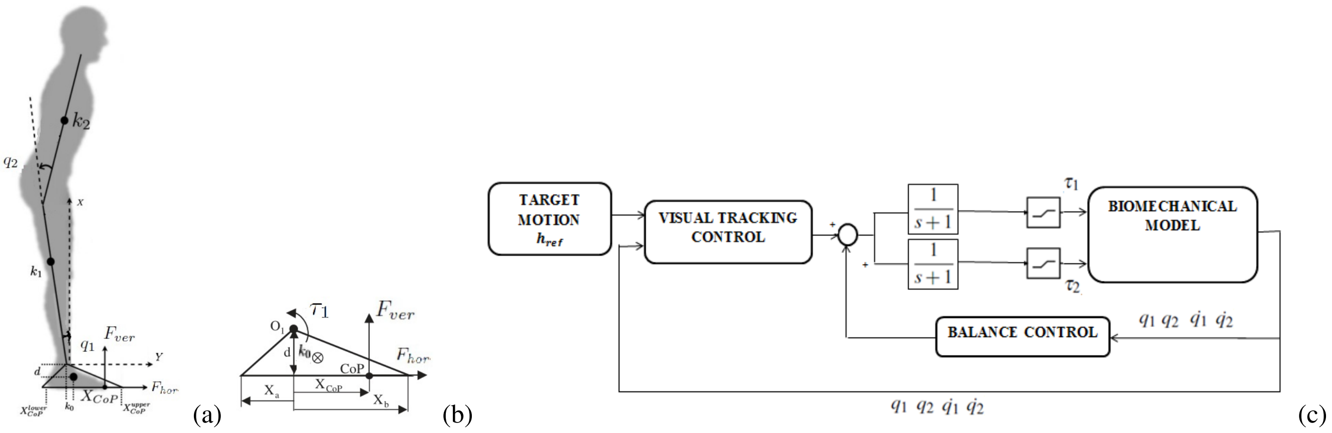

Fig. 1. (a) DIP model in sagittal plane. (b) Characteristics of ankle-foot group. (c) Controller block diagram for postural coordination

where (k_{p11}, k_{p12}, k_{p21}, k_{p22}), (k_{d11}, k_{d12}, k_{d21}, k_{d22}) are the proportional and derivative gains respectively, of the balancing PD controller, and (k_{p1}, k_{p2}), (k_{d1}, k_{d2}) are the proportional and derivative gains respectively, of the PD controller that accomplishes the head tracking task. $\Delta x = x_0 - x$, where x_0 represents quite standing (angular position and velocity are both equal to 0). $\Delta h = h_{ref} - h(x)$, where h_{ref} is system input represented by target's position and h is the subject head position.

III. GAIN SYNTHESIS

A. Optimal control

Movement planning assumes that humans perform a motion according to certain optimal criteria, i.e. the movement control can then be related to a problem of cost function minimization. In this study the visual tracking task is transformed into a mathematical optimization problem with an objective function that specifies the minimization of the torques sum.

$$\underset{K}{\text{minimize}} \quad J(K) = \frac{1}{2}\int_{3T_c}^{4T_c} \left(\tau_1^2 + \tau_2^2\right) dt \tag{7}$$

$$\text{subject to} \quad h(3T_c + \tfrac{1}{4}T_c) - a_{ref} = 0, \tag{8}$$

$$h(3T_c + \tfrac{3}{4}T_c) + a_{ref} = 0, \tag{9}$$

$$\forall t \in [3T_c, 4T_c],\ X_a \leq X_{CoP}(t) \leq X_b. \tag{10}$$

where $T_c = 1/f_{ref}$ corresponds to the period of the target motion; f_{ref}, a_{ref} target frequency and magnitude; X_a and X_b, as in [4] represent the boundary of the BoS, i.e. extremal positions of the CoP in forward and backward directions with respect to the ankle joint. In Eq.(7), only the fourth period is taken into account because the initial values of joint position and velocity are taken to be equal to 0, hence one should see a transient response that must not taken into account in the optimization process.

B. Numerical experiment

As shown in III-A the aim of this study is to find the optimal feedback control gains, minimizing the sum of torques (7) under two constraints: first (8)-(9), the head needs to move with the target's frequency and to have the same maximum magnitude during the fourth period, and secondly (10), subject's body needs to maintain balance. These two constraints are added to the optimization algorithm as equality constraints for the first ones and as an inequality for the second one. Furthermore, the joint torques are bounded with bound values that are larger than the biological plausible maximum feasible torques. They do not interfere with the optimization process but are used only to prevent the optimization process to run the biomechanical model using too inconsistent gain values.

To perform the visual tracking task, specific input data values were chosen [6]. All optimization trials were done for a typical subject: $height = 1.8m$ and $mass = 75kg$. The anthropometric parameters values were: $d = 0.07m$, $l_1 = 0.88m$, $l_2 = 0.85m$, $m_0 = 2.18kg$, $m_1 = 21.98kg$, $m_2 = 50.85kg$, $k_0 = 0.07$, $k_1 = 0.55$, $k_2 = 0.63$ and the inertia $I_i = m_i(k_i l_i)^2$. The input signal is a sine wave in the cartesian space. In our study two different magnitudes for target's motion are used: 5 cm and 10 cm.

The starting point taken for the feedback gains in the optimization search is almost the same in all simulations. Taking into account that we have 12 gains to find with the optimization program, it is safer to start from a feasible point. In fact, the gains are initialized as follows: the initial values for the balance controller's gains correspond to the ones obtained from actual data in [20], whereas the initial values for the tracking controller are adjusted manually so that the tracking task approximately satisfied.

For each magnitude 7 different frequencies are studied: 0.1Hz, 0.2Hz, 0.3Hz, 0.4Hz, 0.46Hz, 0.5Hz, 0.6Hz and 0.7Hz. The above frequencies were used in the literature for the same experimental paradigm, hence we have chosen them in this study in order to investigate whether our results are consistent [4], [21].

The in-phase/anti-phase transition frequency for each amplitude was numerically found, with a precision of 0.01Hz, by increasing the frequency from 0.3Hz to 0.4Hz. We found a transition frequency at 0.35Hz for 5cm target motion magnitude, and a transition frequency at 0.31Hz for 10cm magnitude.

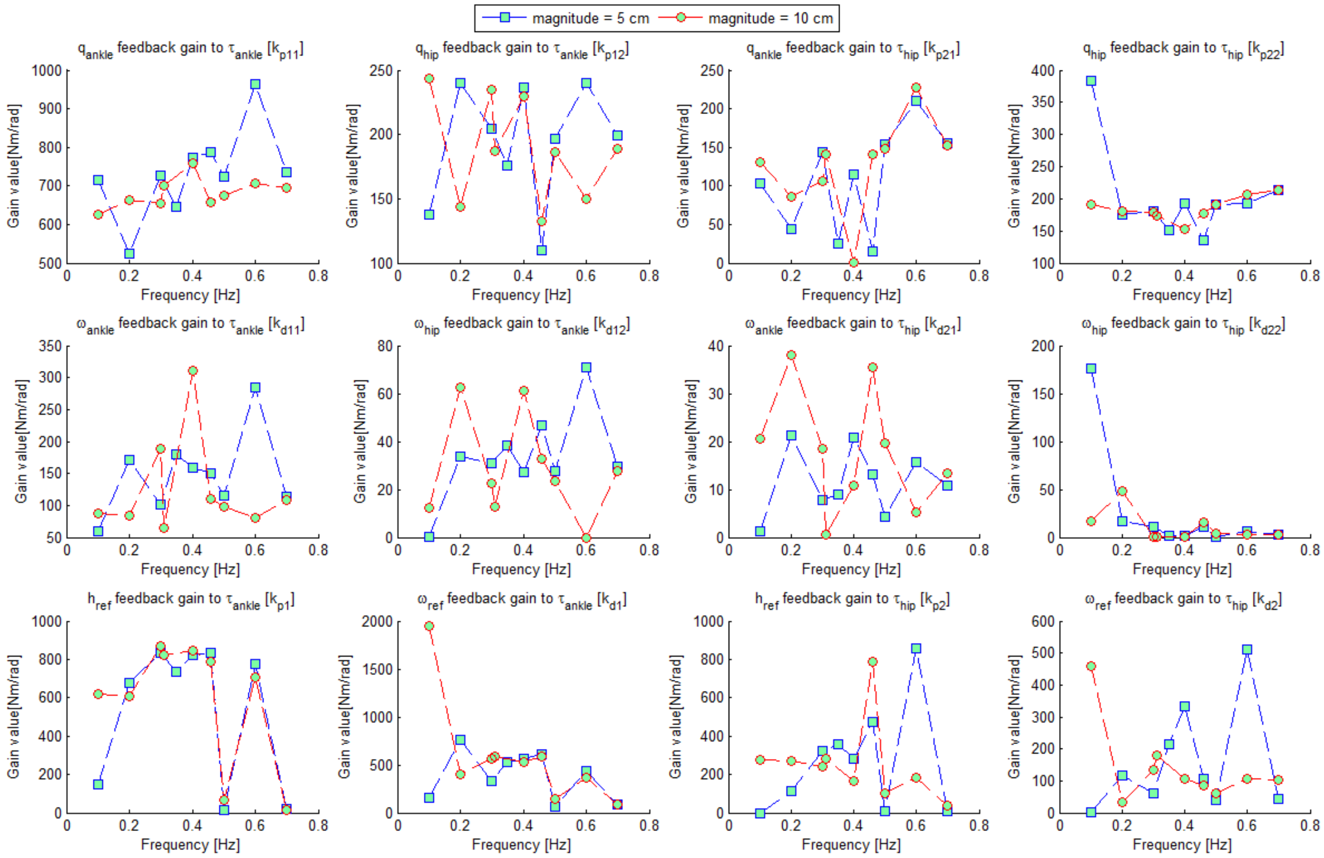

Fig. 2. Gains values for two different values of the input's magnitude (5cm and 10cm) and at different frequencies

C. Analysis

The optimal feedback control gains values obtained via optimization for the two different magnitudes of target displacement (5, 10 cm) and for low/high frequencies (0.1, 0.2, 0.31, 0.35, 0.4, 0.46, 0.3, 0.5, 0.6, 0.7 Hz) are reported on Fig. 2.

Two different postural coordination modes appear on the joint trajectories when increasing the target's oscillation frequency. Fig. 3 presents the optimal results for in-phase (0.1Hz) and anti-phase (0.7Hz).

On the one hand, in-phase coordination mode shows that the ankle joint torque and hip torque extends simultaneously and that the ankle one has a greater influence on the postural coordination modes responses, when the biomechanical constraints are inactive. Yet, on the other hand, anti-phase coordination mode presents the influence of the hip torque at the activation of the biomechanical constraints.

A dependency between transition modes and target's magnitude was found, so when the target magnitude increases, the transition frequency decreases. For a magnitude equal to 5cm the transition frequency is estimated as 0.35hz, and for one equal to 10cm at 0.31Hz. Simulations exhibited angular displacement magnitudes more reduced at ankle joint that at hip one, regardless of the frequency (Fig. 3-5).

During the trials, for low frequencies (below 0.35Hz for 5cm and 0.31Hz for 10cm), the balance constraint i.e. the CoP displacement to remain in BoS (see Fig. 6), is naturally satisfied, and the constraint is not active during the optimization search. [4], [5] has shown that during anti-phase coordination mode, the balance constraint becomes active in the optimization algorithm and that it is this activation that leads to a modification in angular magnitude displacements.

In terms of feedback control gains, the results did not exhibit an explicit relation for the gains scaling (see Fig. 2). It seems that the gains adapt in an independent way for each frequency and magnitude. In fact, the optimization algorithm succeeded in finding the optimal solution and we checked that it converged towards the same solution when the initial values were modified by a substantial amount. Nevertheless, this does not exclude the possible existence of other optimal solutions corresponding to very different gain selection. This does not change the main conclusions of our findings but may need further investigation as regarding the existence of a trend in the gain scaling.

IV. GAIN SCHEDULING

A. Gain prediction for non-studied frequency

The approach proposed in III-C returned the proper gain values only for the following studied target motion frequencies: 0.1, 0.2, 0.31, 0.35, 0.4, 0.46, 0.3, 0.5, 0.6, 0.7 Hz. To predict proper gain values for a new target motion frequency

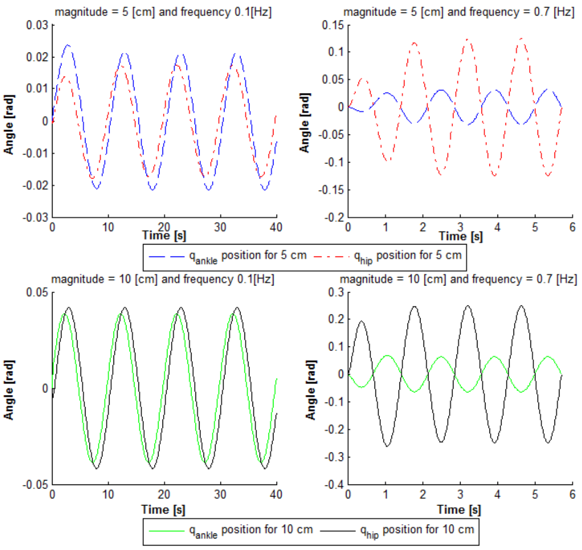

Fig. 3. Angular position; target amplitude = 5cm and 10cm; in-phase (0.1hz) and anti-phase (0.7hz) coordination modes

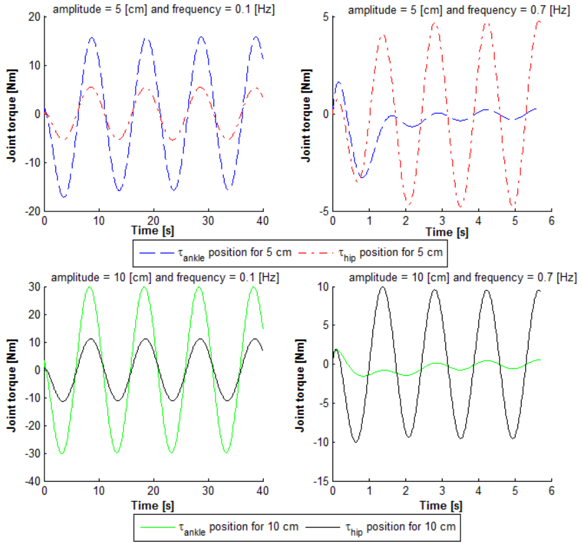

Fig. 4. Joint torque displacement; target amplitude = 5 cm and 10 cm; in-phase (0.1 hz) and anti-phase (0.7 hz) coordination modes

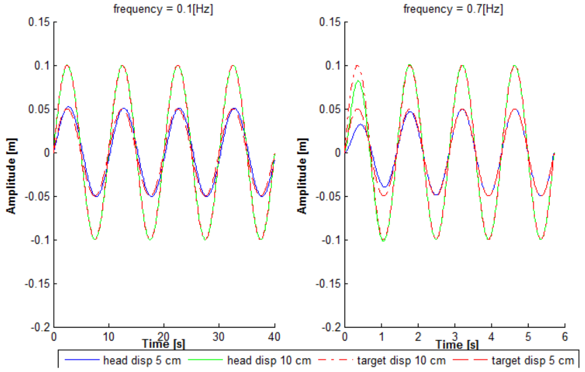

Fig. 5. Head displacement; target amplitude = 5 cm and 10 cm; in-phase (0.1 hz) and anti-phase (0.7 hz) coordination modes

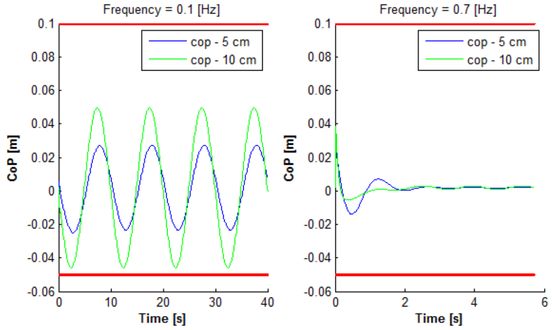

Fig. 6. CoP for two different values of the target magnitude (5 cm and 10 cm) and at different frequencies

for 5cm motion magnitude, we use a polynomial interpolation upon the values obtained for the studied frequencies, i.e. the values depicted on Fig.2.

Using the so-predicted gain values in closed-loop, our controller exhibited consistent performance, i.e. it achieved a very good tracking of target motion while keeping CoP within BoS boundaries, hence balancing. Furthermore, it showed in-phase coordination mode for frequencies lower than the phase transition frequency, i.e. $f < 0.35$Hz, and showed anti-phase coordination mode for frequencies larger than the phase transition frequency, i.e. $f > 0.35$Hz.

B. *Frequency sweep*

In this subsection, target displacement is taken as sine waveform with a linearly varying frequency (0.1, 0.15, 0.2, 0.28, 0.3, 0.35, 0.4, 0.46, 0.5, 0.6, 0.7 Hz) and a constant amplitude (5 cm), as shown on Fig. 7.

Using controller gain values computed as in subsection IV-A, we were capable of scheduling gains for our controller in order to track the moving target with varying frequency while keeping balance.

Figs. 7-10 show the performance obtained using this gain-scheduling approach. One can see that the visual tracking task is achieved (Fig.7), the coordination mode transition takes place at the correct frequency value, i.e. at $t = 40$s on Fig.9 : ankle strategy is replaced by hip strategy, hip torque increases and dominates ankle torque (Fig.8). In addition, CoP remains within BoS during whole period.

V. CONCLUDING REMARKS

In this paper, we investigated human simultaneous tracking a moving visual target and balancing in an optimal control framework.

We showed that this experimental paradigm can be efficiently modeled combining a linearized DIP with two parallel PD feedback loops generating, independently, joint corrective torques in the joint articular space, in order to achieve a task defined in the cartesian space. Our model did not include visual and sensory integration. Future studies will investigate the impact of a more thorough modeling including these visual and sensory integration processes.

For each studied frequency, our gain synthesis procedure yields values that makes the closed-loop system behave

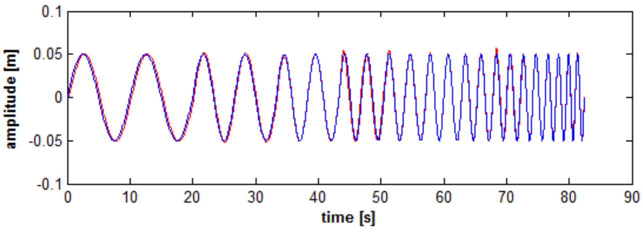

Fig. 7. Target and head displacement for a target amplitude = 5 cm and increased frequency

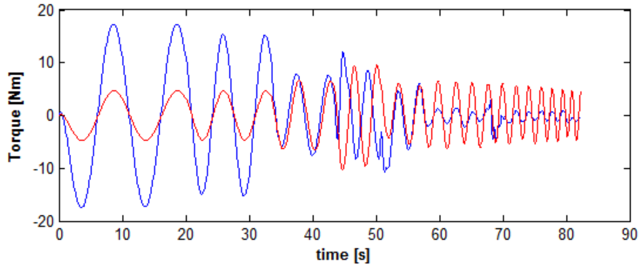

Fig. 8. Torque displacement for a target amplitude = 5 cm and increased frequency

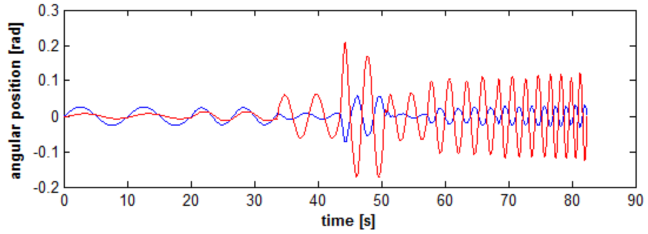

Fig. 9. Ankle/Hip angular position for a target amplitude = 5 cm and increased frequency

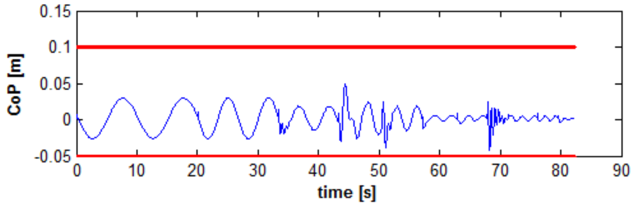

Fig. 10. CoP displacement for a target amplitude = 5 cm and increased frequency

as in actual experiments, i.e. it tracks the moving target while balancing, exhibits appropriate coordination mode and in-phase / anti-phase transition. Indeed, the gain synthesis approach may be related to muscle actuation synergy and coordination that are produced by the human motor control system.

Predicting controller gain values via interpolation, we developed a gain-scheduling approach that successfully achieved the task for both a varying and unexplored moving target frequencies. Interestingly, our gain-scheduled linear PD controllers acting in parallel were capable of achieving the task analyzed. Clearly, such an approach may have potential applications in humanoid robotics, and may also be used to characterize more complex postural tasks or cyclic walking motions. Further studies will address ways to extend this approach to other kind of motions, such as non-periodic motions.

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