Modeling postural coordination dynamics using a closed-loop controller

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Abstract—This paper models recent data in the field of postural coordination showing the existence of self-organized postural states, and transition between them, underlying supra-postural tracking movements. The proposed closed-loop controller captures the complex postural behaviors observed in humans and can be used to implement efficient and simple balance control principles in humanoids.

I. INTRODUCTION

Due to their anthropomorphic structure, humanoid robots often present dynamic similarities with humans. Hence the fields of humanoid robotics and of human movement science can inspire each other. In 1985, Nasher and Mc Collum [1] observed two postural strategies at the muscular activation level, when the whole upright body reacts to an external perturbation: The ankle strategy which is characterized by a large activity of the ankles and the hip strategy which corresponds to the coordinative activation of the hips and the ankles. These postural strategies have inspired the development of a bio-inspired balance controller allowing a humanoid robot to recover from large disturbances and still maintain an upright posture [2], [3].

Within the framework of coordination dynamics [4], Bardy et al. [5] analyzed the whole body joint coordination in the sagittal plane during a visual tracking task. They proposed the use of a collective variable to describe in a simple way the complex biological -segmental, articular, muscular- couplings. They had standing participants moving back and forth in the sagittal plane in order to track the displacement of a virtual target. This simple task allowed the observation of several self-organized properties of the postural system, such as phase transition, multistability, critical fluctuations, hysteresis, and critical slowing down. The collective variable able to capture both fully and in a very compact way these properties is the relative phase, i.e. the phase difference between the ankle and the hip. Two coordination modes were observed between ankle and hip depending on the target’s frequency: An in-phase mode for low frequencies and an anti-phase mode for high frequencies.

Martin et al. [6] used a double inverted pendulum (DIP) as a biomechanical model within a constrained optimization process to analyze Bardy et al.’s results, and showed that the location of the center of pressure (CoP) can drive the selective of the coordination mode.

In a previous work [7], we studied in more details Bardy et al.’s with a method similar to the one used in [6] and implemented the obtained coordination modes in the HOAP-3 and HRP2 humanoid robots. We showed that the in-phase mode corresponds to the minimum energy mode for low frequencies and that the anti-phase mode is the only one able to maintain balance for high frequencies. In our simulations, the anti-phase mode was selected when the CoP reached the base of support (BoS) limits. This result may be used to improve the control of balance control in humanoid robots.

However, the approach described above considers only steady state behaviors and thus is not capable of capturing the transient dynamics observed during human postural behaviors such as the hysteresis phenomenon for instance. Non-linear coupled oscillators are classically used to model these human dynamical coupling phenomena [8]. However, these oscillators involve several unknown parameters which have to be identified and whose connection with the actual system is difficult to delineate.

The goal of this paper is to propose a non-linear closed-loop model of the supra-postural behavior documented by Bardy, which is composed of a double inverted pendulum as biomechanical model, a classical controller proportional-derivative and a dynamical (time-varying) torque saturation to ensure robot’s balance. The ability to reproduce the biological couplings should ameliorate or simplify balance control in humanoids.

The structure of the paper is as follows. Typical results from an human postural tracking task experimentation are depicted in section II. The proposed closed-loop modeling is described in section III. Section IV contains the comparison between simulations, obtain with the closed-loop modeling, and human observations. Finally, the analysis of the simulations results are given in section V.
II. HUMAN EXPERIMENTATION

The main objective of this experiment is to collect human data that will be qualitatively compared with the result simulations performed in section III.

A. Methods

The task used in this experiment is based on the experimental paradigm previously used in literature [9], [10] consisting in tracking a moving target with the head while standing. Participants stood on a force platform in front of a real target moved by a linear motor in antero-posterior direction, with the knees locked and the soles in permanent contact with the ground (Fig. 1, 2, 3).

The experiment was performed on 11 healthy male subjects, with mean age 25, mean weight 75kg and mean size 1.79m. The motion of target was sinusoidal with 10cm as amplitude, the frequency increases from 0.1Hz to 0.65Hz by 0.05Hz steps and during 10 periods. To capture the joint positions, a motion capture system (VICON NEXUS MX13) was used, with 8 cameras trasking 15 makers on the right side of the subject.

Fig. 1. Experimental device. Physical target moved by a linear motor, force plate and motion capture device.

B. Experimental results

Fig. 4 shows typical results for a representative subject (75kg, 1.80m).

On (Fig. 4a), the mean values of the (Hilbert-transformed) relative phase between ankle and hip positions are represented as a function of the frequency step. The depicted error bars correspond to the standard deviations during the 10 oscillations achieved at each frequency step. A transition is observed from in-phase to anti-phase mode around 0.4Hz.

Joint positions are presented on Fig. 4b by minima and maxima values. Each point is the mean value of the maximum (or minimum) joint position reached during the 10 oscillations performed at each frequency step. Hip position is larger than the ankle position. The hip amplitude is larger than the ankle amplitude for the anti-phase mode as mentioned in [11], [10].

Fig. 4(c) depicts mean values for torque amplitude estimation. Ankle torque is larger for in-phase mode and inversely for anti-phase mode.

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Joint positions are presented on Fig. 4b by minima and maxima values. Each point is the mean value of the maximum (or minimum) joint position reached during the 10 oscillation periods performed at each frequency step. For the in-phase mode, i.e., at low frequencies, the joint positions amplitude difference are small, with large individual differences in terms of joint amplitude. The hip amplitude is larger than the ankle amplitude for the anti-phase mode as mentioned in [11], [10].

Fig. 4(c) depicts mean values for torque amplitude estima-
tion at each frequency step. Torque values were estimated by using the inverse dynamical model of the DIP. They indicate a larger ankle torque amplitude for in-phase mode and a larger hip torque amplitude for anti-phase in agreement with the ankle and hip strategy reported in [1] and by Runge et al. [12].

These observations were observed for all participants and are in accordance with [9], [5], [11], even though the actual transition frequency and joint amplitudes depend on the specific subject body type.

III. MODELING POSTURAL BEHAVIOR

A. Biomechanical model

Barin [13] shows the relevance of a inverted pendulum structure in the case of a human sagittal plane task. In addition, the Bardy’s paradigm focussed on the hip and ankle joints, so a DIP in the sagittal plane is used as a biomechanical model (Fig. 5).

In the task space we only set the horizontal head position, so the actuated system is redundant with respect to the task.

Fig. 5. Double inverted pendulum used to model postural coordination

Balance is described by the position of the CoP within the BoS, which can be expressed as a function of the dynamic parameters (eq.1).

\[ X_{CoP} = \frac{(\Gamma_1 - F_{gx}d + m_0k_0g)}{F_{gy}} \] (1)

where \( F_{gx} \) is the horizontal ground reaction force, \( F_{gy} \) the vertical one, \( \Gamma_1 \) the ankle torque, and \( m_0 \) and \( k_0 \) foot parameters. Euler’s equations were used for the calculation of the ground reaction forces as proposed by Cahouet et al. [14].

B. Closed-loop modeling

In the robotics field, many control schemes exist for redundant applications. Whitin the framework of the operational space formulation defined by [15], Sentis [16] proposed a task-posture decoupling for humanoids. This controller enables humanoids to execute tasks in operational space, and at the same time, to control the CoP location.

Inspired by classical work on postural strategies, a decoupled controller with a specific control on the CoP location was proposed by [3]. We accept that the instantaneous control of the CoP is necessary in many applications, but in the case of Bardy’s paradigm, we focussed only on the human observations. In the human motor-control literature, there are no obvious evidences that the CoP location is directly controlled by the central nervous system. In addition [6], [7] emphasized the fact that human postural system changes its coordination mode when the CoP reaches the BoS limit.

Fig. 6. Typical CoP displacement for one step frequency (0.55Hz). The CoP location is bound by lower BoS limit.

Fig. 6 presents a typical CoP trajectory for one frequency step, during the experiment with humans. It is clear that the CoP location is saturated due to the BoS and a limitation of the human ankle torque. The following control scheme takes into account these observations with a non-linear closed-loop modeling, which is composed of a double inverted pendulum as biomechanical model, a classical controller in operational space, and a dynamical torque saturation to ensure robot’s balance.

On Fig. 7, \( DKM \) is the direct kinematics model, \( K_{pj} \) and \( K_{dj} \) are the proportional and derivative controller gains in the joint space, \( J^+ \) is the pseudoinverse matrix and \( \Gamma_{1Sat} \) the dynamical ankle saturation.

It is well attested that the use of the pseudoinverse matrix
in kinematics redundant problems minimizes the norm of the velocity vector $||\dot{\theta}||^2$ at a given time. By analogy with inverse kinematics, the pseudoinverse matrix used in the control scheme depicted on Fig. 7 minimizes the norm of the torque vector $||\Gamma(t)||^2$.

To complete the modeling, the issue of maintaining the CoP inside the BoS needs to be addressed. Since the CoP is a function of the ankle torque (see eq. 1), we propose to use a dynamical torque saturation for the ankle. Note that the use of the saturation loop does not imply the control of instantaneous CoP location. At each time step, the thresholds for ankle torque saturation maintaining the CoP inside the BoS limits were computed. In the following equations, the upper threshold for torque saturation is given by

$$\Gamma^{\text{upper}}_{1,\text{Sat}} = F_{gy}d - m_0k_0g + X^{\text{upper}}_{CoP} F_{gy}$$

where $X^{\text{upper}}_{CoP}$ is the upper BoS bound, $m_0$ and $k_0$ are foot parameters, and the lower one is given by

$$\Gamma^{\text{lower}}_{1,\text{Sat}} = F_{gy}d - m_0k_0g + X^{\text{lower}}_{CoP} F_{gy}$$

where $X^{\text{lower}}_{CoP}$ is the lower BoS bound.

Finally, if at a given time previous step, $\Gamma_1$ is saturated then the postural system acts mainly on hip torque in order to execute the task. Eventually, it will change the coordination mode.

C. Consideration of the human joint properties

The human upright stance depends on the control of torques at ankle and hip levels, in the case of the DIP. In humans, the joint torques are produce by muscle contractions. Therefore, the muscle (joint) stiffness is largely studied and its role in control mechanisms involved in human stance is the target of a vivid debate. However there is converging evidence showing that joint stiffness is not completely controlled by the CNS but is partly determined by a local control loop and mechanical joint properties (i.e., muscles viscolelastic properties and joint friction). These active and passive components of stiffness depend on the level of muscle contraction in addition to the joint angle and angular velocity, and are mechanically indistinguishable.

To improve the fitting of human joint positions by the model, we use a simplified representation of human joints. Passive spring damping systems are added to the rigid DIP. Currently, the stiffness and the viscous coefficient friction of joints are kept constant. But in future works, we will implement an active and variable joint stiffness, as a non linear muscle model.

IV. FIT BETWEEN MODEL AND HUMAN DATA

The simulation results obtained with the closed-loop controller are presented in this section. Simulation parameters are given for the same typical subject and the same frequency evolution described in section II. The length of the foot is 20cm. The controller’s gains and passive spring damping coefficient are constant during the simulation.

On Fig. 8a, one can see two distinctive coordination modes similar to the ones exhibited in humans and reported in section II. The in-phase mode between the ankle and the hip appears at low frequencies and the anti-phase mode appears at high frequencies. Note however that the transition between them occurs around 0.5Hz in our simulation whereas it occurred around 0.4Hz in the human experiments.

This discrepancy may be induced by the approximate nature of the model used.

Fig. 8b shows that at low frequencies, the joint positions for hip and ankle have similar amplitudes. This result is fairly close to the one observed with humans (see Fig 4b). At high frequencies, i.e. for the anti-phase mode, simulation results show a larger motion for the hip than for ankle position as observed in the human data.

Considering now the joint torque amplitudes (Fig. 8b), the ankle torque is larger than the hip torque for in-phase, a result that is reversed for anti-phase, in accordance with the human observations.

One can see that our closed-loop model is able to reproduce the human postural observations. An optimization process to tune the gains of the closed-loop system would bring more precision for the human data fitting.

V. ANALYSIS OF THE TRACKING TASK

A. Relative phase transition analysis

In order to further analyze the behavior of the closed-loop scheme, the target frequency was up-chirped from 0.1Hz to 1Hz in our simulation. The subject parameters was the same typical as in section II. Two cases are considered here. In the first case, the dynamical torque saturation is activated and the results are depicted on Fig. 9. In the second case, the
dynamical torque saturation is disabled, the results are given on Fig.11.

Fig. 9. Ankle/hip relative phase (a), joint torque (b) and CoP motion (c). Transition frequency occurs at 0.5Hz when the dynamical ankle saturation is activated. Hip torque is larger than ankle torque for the anti-phase mode. The CoP constraint is able to guide the coordination mode.

Fig. 9 shows the Hilbert relative phase on the simulation results, the joint torques and the CoP location. We can see that the CoP stays inside the BoS limits (Fig. 9c) and that when it reaches these limits the coordination mode suddenly changes from in-phase to anti-phase mode (Fig. 9a). This is in agreement with previous works [7], where we show on humanoid robots (see Fig. 10) that the anti-phase mode is the stabllest mode.

Finally the hip torque is larger than the ankle torque (Fig. 9b).

On Fig. 11, one can see that a change in the coordination mode occurs even when the CoP constraint is disabled, but at a higher frequency (0.6Hz) compared to Fig. 9 where the CoP constraint is activated. In fact, since the pseudoinverse matrix, in the closed-loop scheme, minimizes $||\Gamma(t)||^2$ the system reaches the minimal energy solution. So in the redundant case our controller with the pseudoinverse matrix behaves like an optimal controller.

Fig. 10. HRP2 experiments with in-phase coefficients at high frequency ($f = 0.6Hz$, $BoS = 2cm$, $A_t = 4cm$). The robot cannot maintain its balance and falls backward.

B. Effect of intrinsic dynamics on coordination mode

The intrinsic dynamics, mechanical parameters, of the DIP may have an impact on the adopted coordination mode. We proposed to study the energetic cost of the in-phase and the anti-phase mode. An optimization process was used with (eq. 4) as cost function and with an averaging method on a oscillation period.

$$J = \int_0^T \left( \left( \frac{d\Gamma_1}{dt} \right)^2 + \left( \frac{d\Gamma_2}{dt} \right)^2 \right) dt$$  \hspace{1cm} (4)

The retained cost function was the minimum torque change. It is known to represent adequately the energetic behavior in human tracking tasks [17]. A constraint was added on the relative phase in the optimization process. The optimal solution at each frequency was computed by forcing the system to remain either in the in-phase mode or in the anti-phase mode. The solutions obtained are presented on (Fig. 12) for in-phase (blue dot line) and anti-phase (green dot line) mode.

For low frequencies, one can see that the in-phase mode minimizes the torque change criterion. This result is in accordance with our previous work [7]. Conversely, it is clear that the anti-phase mode minimizes the torque change criterion at high frequencies. These results show the impact of the energetic criteria in the emergence of human postural coordination modes.

C. Hysteresis phenomenon

An hysteresis phenomenon, hallmark of non linear systems, has been observed in human experiments [9]. In the postural coordination framework, the hysteresis phenomenon has never been modeled. The closed loop modeling introduced in this article exhibits such an hysteresis phenomenon when the target frequency is up-chirped and then down-chirped (Fig. 13). Note that the gain values of the controller and the dynamics of
the reference target influence the hysteresis region. Current work now examines the energetic cost for different types of reference dynamics around the transition frequency in order to better understand the hysteresis phenomenon.

![Graph showing energetic response per frequency step for in-phase or anti-phase coefficient. The optimization process choose the optimal coefficient, in-phase (blue dot line) coefficient only and anti-phase (green dot line) coefficient.](image)

**Fig. 12.** Energetic response per frequency step for in-phase or anti-phase coefficient. The optimization process choose the optimal coefficient, in-phase (blue dot line) coefficient only and anti-phase (green dot line) coefficient.

The closed-loop modeling also allows to reproduce the hysteresis phenomenon observed in human experiments.

By now, we believe that our model of postural coordination is promising in capturing behavioral invariants observed in human postures.

A similar framework used by [2] for decoupled control tasks are able to reproduce a wide range of adaptive behaviors. That the reasons why we believe they are appropriate for humanoid robotics.

The closed-loop controller is currently under development on humanoid robots HRP2 and HOAP-3. However a low-level adaptation is necessary since we use a torque control vector while most humanoids are controlled in position via a local regulator.

The disturbance rejection properties of our controller are being characterized. This controller will be able to automatically change the phase difference and the joint amplitude necessary to maintain balance.

**REFERENCES**


VI. CONCLUSIONS

The closed-loop controller model we have developed, provides realistic predictions of postural sway movements during head tracking task.

The computed results are consistent with human observations related to similar experimental paradigms. Many of the differences between experimental and simulated results can be attributed to simplifications in the modeling.

The closed-loop modeling approach offers a better comprehension of the postural coordination phenomena.

The results obtained when varying simulation parameters, show that the sudden bifurcation emerges from both equilibrium constraint and cost minimization.