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Prediction in the context of a human-inspired posture control model

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HIGHLIGHTS

- A human inspired algorithm for posture control is implemented and tested in a 14 DoF Humanoid robot.
- The control framework includes prediction; The control system is active while the prediction model is learnt and used in the control loop itself.
- The on-line and the off-line training produce different sets of parameters.
- The implementation of a predictor for external disturbances in this context is described, tested and discussed.
- The choice of online training proved to be advantageous in terms of quality of prediction and robustness of the stability of the control loop.

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ABSTRACT

Maintaining an upright stance is a challenging task in both humans and humanoid robots in that it is complicated by inherently unstable mechanics and requires controlling a noisy, inaccurate, multi-DoF system. Hence, learning and prediction are often involved in humanoid control. This appears to apply similarly in humans where continuous control with sensory feedback avoids falling. This work presents an attempt of integrating a learned predictor into a humanoid posture control. A neurorobotics approach was used, in which the concept of a bio-inspired modular control is tested on a 14 DOF humanoid robot platform. In particular, the paper shows how to address, in a closed loop system, the problem that sensory feedback tends to create a correlation between the state of the system and its controlled inputs. This complicates the training of machine learning models, or identification procedures in general, because the feedback makes the effect of the noise, which is unknown, on the system output dependent on the input. Using a bio-inspired modular control of the robot, a linear predictor based on on-line learning, integrated in the control through a bio-inspired schema, has been compared with the method of a Smith predictor. The on-line predictor compared favorably with the Smith predictor in the task of balancing during voluntary movements.

1. Introduction

1.1. Overview

The embodiment of human-inspired sensorimotor control in robots is a powerful experimental tool of neurorobotics [1]. The robots used for this purpose were designed with human-inspired anthropometrics, sensors and actuators. Hypotheses of human posture control were implemented and evaluated by comparing the robots performance with that of human subjects within a real world set-up [2,3]. The comparison between bio-inspired control methods and humanoid control systems can be a source of inspiration for both the research fields, e.g. see [4,5] for comparisons between bio-inspired and "technical" humanoid posture control systems. In the future, humanoid control may profit from human solutions, because human performance is still superior to that of humanoids in many tasks [6]. Recently, the evaluation of human likeliness has attracted attention as a research topic [7,8], in this framework human-inspired posture control models can provide a reference for comparison and suggest which basic skills should be tested for benchmarking. In this work, a neurorobotics approach was used to further develop a human-inspired modular concept of posture control with disturbance prediction.

Two states exist in human postural control of biped stance: quiet stance and perturbed stance. In quiet stance, the body's center of mass (COM) is oriented vertically over the ankle joint. Spontaneous sway data then shows dead bands in mechanics and control, i.e. a band of input values (physical stimuli and associated sensory inputs) for which the response of the system, in this case joint torques, is zero. This may have contributed to the notion that the sway reflects intermittent control [9]. Notably, we will deal here with perturbed stance (COM is slightly shifted forward [10]), in which the balancing can be described by continuous control [11].

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The spontaneous sway in this situation is mainly caused by sensory noise and to a less extent by motor noise [12]. Although this noise may have some beneficial effects such as prevention of sensory adaptation, it may endanger control stability. For this reason neuroscientists hypothesize a shift in the control from continuous sensory feedback control to a less noisy prediction signal occurs whenever possible (e.g., with voluntary movements; see below). However, a neurorobotics implementation faces problems. For example, an important problem is that non-linearities such as static friction in the mechanics of a multi-link humanoid are often insufficiently known, making it difficult to implement a full human biomechanical model in the prediction. The solution chosen here is to apply machine learning in the robot and to postulate that humans also employ some kind of learning system which successfully deals with on-line learning in a continuous feedback control system. This system faces two problems: (1) the feedback into the systems input is a function of the measured output, and (2) using the prediction in the control loop in turn changes the system's learned response, which presents the risk of making erroneous predictions and rendering the control unstable. The presented experiment explores how training can cope with (1) and how to apply an on-line training when the prediction is used in the control loop, so that the system learns the dynamics of the control with the prediction in the loop, which helps to cope with (2).

These issues in identification of dynamic systems with feedback loop have been considered in general control theory [13] and in machine learning [14]. In the field of robotics several types of learning systems have been used (see for example the survey in [15]). In this work the concept is analyzed in the specific context of a posture control inspired by biological systems.

Biological systems are affected by delays, and it is known that the human nervous system uses prediction to overcome this problem. The prediction can be performed both on self-produced and external disturbances. With self-produced disturbances humans may learn the sensory input produced by an action, while with external disturbances the subject may learn to predict some pattern of repetitive stimuli (e.g. a periodic motion of the support surface) or may predict a forthcoming stimulus on the basis of clues. Predicted sensory signals may be advantageous not only in terms of shorter time delay but also in terms of higher accuracy [16].

In the following, we briefly describe the bio-inspired modular control system used in the robot, called disturbance estimation and compensation (DEC) system [17,18], as well as the integration of disturbance prediction in the DEC control, the robot used for implementation, the model used to implement the prediction, and the experimental results, comparing different possible solutions.

1.2. *The DEC concept*

The DEC concept provides a descriptive and predictive model of how human postural control mechanisms interact with movement execution control in producing a desired movement [17]. The following list outlines the basics (compare Fig. 1): (a) A servo control loop with joint angle proprioceptive feedback exists for any degree of freedom (DoF) in the human skeletal sensorimotor system, executing at the output the joint torque that is commanded at the input. (b) Multisensory mechanisms estimate the physical factors which may disturb the servo. These disturbances are *rotation* (1) and *translation* (2) of the supporting link or support, contact forces such as a push (3) and field forces such as gravity (4) impacting the supported link. (c) The disturbance estimates are fed into the servo such that the joint torque on-line compensates for the disturbances while executing desired movements. (d) The disturbance compensation mechanism allows the system to maintain a low loop gain and thus stable control in face of neural time delays as well as high mechanical admittances to passive link motion. In balance control of upright stance, for example, the loop gain is maintained at a level just high enough to prevent falling by a mechanism called "sensory re-weighting" (see [11]). The sensory re-weighting produces a nonlinear response that can be predicted by the DEC control [2,3].

In neurorobotics experiments, human responses to support surface tilt were compared in the same set-up with responses of a DEC-controlled single inverted pendulum (SIP) robot swaying about the ankle joints in the sagittal plane [2]). In similar experiments using a double inverted pendulum (DIP) robot, a combination of two DEC modules controlled hip and ankle joints, and human-likeness of performance was demonstrated using system identification methods [3]. A generalization of the DEC concept for a modular control architecture was developed, in which the estimators in each module treats the disturbances produced by all supported links as if stemming from a SIP [18]. The reference input into each module determines its postural function (e.g. maintaining a given orientation of the supported link either in space or with respect to the supporting link, or maintaining the COM above its supporting joint). The modules in this architecture exchange information with neighboring modules corresponding to their mechanical interconnections, thereby forming an internal model of the body in its current configuration. Here, work with a 14 DoF robot is presented with the aim in mind to study, in future, the combination of voluntary movements and posture control and to investigate how the full body control emerges from the interaction between modules.

1.3. *Testing prediction in the framework of the DEC concept*

In neuroscience, experimental evidence suggests that sensorimotor action is internally monitored, using a copy of the motor command, often called the efference copy (EC) [19], to distinguish unforeseen external from self-produced sensory inflow. Engineering considerations about control stability in the face of the considerable feedback time delays in biological systems additionally emphasize the predictive property of EC, inspired by the technical Smith predictor [20,21]. Furthermore, noise reduction by state prediction is an issue, and observer models are currently used to address these three and further control issues [16]. These three issues are also constituents of prediction within the DEC concept [17]. A brief description of the principle is given here with respect to the neurorobotics experiments described below, where the robot performs a voluntary body lean in the sagittal plane, while standing on firm support. This task represents a simple and instructive example. Prediction in the gravitational torque estimators (Fig. 1) provides feed forward compensation for the need of increased gravitational ankle torque, while the counteraction of any passive lean-evoked increase in ankle joint torque continues. In general, the DEC control, as described in previous works (see [22]), stabilizes the body not only during quiet stance, but also during voluntary movements. The proposed simple task provides a working example that allows for comparison between cases with and without prediction. As a further test an additional delay is added in the control loop to test the robustness of the implemented solution.

In the DEC concept [17], notably, prediction is not applied to sensory signals directly but to sensory-derived disturbance estimates. A variant of the Smith predictor was used, but the learning of the prediction signal was not included into the modeling. In this work the prediction learning will be implemented and tested in a DEC controlled robot.