Human-like Humanoid Robot Posture Control

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Abstract: This paper validates experimentally a humanoid posture control concept from neuroscience, called disturbance estimation and compensation, DEC concept. The DEC control system, different from typical state estimation systems, is not including a dynamic model of the body. Also, among human posture control models it is particular in that it uses feedback of multisensory disturbance estimates for compensation, rather than 'raw' sensory signals. To this end, the system performs fusions of sensory inputs such as *vestibular inputs* (IMU) and proprioceptive inputs (joint position and speed). The compensation of external disturbances allows the control to use low loop gain, with human-like tolerance of time delays and mechanical compliance. This paper validates the control concept experimentally, measuring the balancing of biped stance of a humanoid 2 DOF robot, Posturob II, while superimposing on support surface tilt either voluntary trunk bending or push stimuli. The results show that the control concept is robust and able to stabilize the robot's balance in complex disturbance conditions. Furthermore, several human-like features such as hip-ankle coordination emerged from the control concept.

1 INTRODUCTION

Humanoid robots require bipedal balancing in many tasks such as walking, which is different from traditional industrial robots that are fixed to the support, not requiring mobility to perform their tasks. Currently, humans are still superior to robots with regard to robustness and versatility in the control of bipedal balancing (Nori et al., 2014). Human-likeness of bipedal control is nowadays an important research topic (Torricelli et al., 2014). Humanoid balancing is often based on the *zero moment point* control or related measures, which try to keep the center of pressure within the base of support under the feet (Goswami, 1999). For this purpose, robots are often equipped with torque sensors or contact force sensors to control such quantities directly (Cheng et al., 2007). However, some kind of inertial measuring unit (IMU) system is required to allow the robot to balance without making assumptions about the support surface. In this paper, the compensation of external disturbances is based on the control of joint torques using a human inspired vestibular system (Mergner et al., 2009) that senses the position of the robot in space and integrates it with signals from other sensors such as joint angle encoders.

The model used in this work is the DEC (disturbance estimation and compensation) model (Mergner, 2010). It is based on studies of human posture control and movement perception. Postural control allows humans to make their voluntary movements smooth and skillful. Postural adjustments provide the movement buttress that the action-reaction law of physics prescribes and maintain body equilibrium by balancing the body's center of mass (body COM) over the base of support. Impairment of posture control in humans tends to produce severely disabling syndromes such as ataxia caused by damage of the cerebellum or sensory systems, with jerky and dysmetric movements and postural instability (Bastian, 1997).

Various models of human posture control have been proposed. These posture control models differ in the approach to internally reconstruct the external disturbances. One is a control engineering approach that relates known postural response criteria to external disturbances using internal model-based methods (van der Kooij et al., 1999; Kuo, 2005). The other approach is mainly biologically inspired, trying to reproduce human response data in model simulations. In a reductionist approach, the Independent Channel, IC model (Peterka, 2002) describes human reactive sway behavior as the result of three sensory feed-

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back loops (vestibular, joint angle proprioception, vision). Changes in disturbance magnitude and modality as well as sensor availability are accounted for by the experimenter using sensory re-weighting rules. The here considered DEC model uses sensor fusion-derived internal reconstructions of the external disturbances having impact on body posture. The sensory re-weightings in the DEC model occur automatically through inter-sensory interactions and non-linear processing in the estimators.

Both the IC and the DEC model originally were restricted to human balancing responses to moderate disturbances in the sagittal plane around an axis through the ankle joints. This allowed simplifying the body biomechanics as a single inverted pendulum, SIP. In this form, the DEC model was re-embodied into a SIP postural control robot (Mergner et al., 2006). The robot was successfully tested in the human test bed (Mergner et al., 2009), reproducing the human responses to external stimuli in various disturbance scenarios and changes in sensor availability (Maurer et al., 2006; Schweigart and Mergner, 2008; Mergner et al., 2003; Cnyrim et al., 2009; Mergner et al., 2009). Further development of the DEC model included its preliminary extension to double inverted pendulum (DIP) biomechanics, adding hip joints to the ankle joints. This allowed investigating the human control underlying the coordination between hip and ankle joint using a hip joint control and an ankle joint control interconnected by sensory signals (Hettich et al., 2014). Furthermore, the DEC control also was generalized for multiple DOFs and tested in simulations (Lippi et al., 2013). In this paper, the control system is further validated using the Posturob II platform by superimposing two external disturbances as well as an external disturbance with a voluntary lean.

In the following, Section 2 presents the general concept of the DEC model. Section 3 describes the experimental setup. The results are presented in Section 4. Finally, conclusions are made and outlooks into the future are given in Section 5.

2 DISTURBANCE ESTIMATION

The DEC model is based on inter-sensory interactions (Mergner, 2010). It evolved from neuroscience research on human perception of self-motion and biped balancing to external disturbances. The concept was developed in an iterative process using balancing experiments and model simulations. The concept uses estimates of external stimuli that provide the feedback to the controller.

Figure 1 gives an overview of the DEC controller with a control module for whole body COM balancing in the ankle joints of the robot and a second DEC module to control trunk-space (TS) orientation in the hip joints. Each module contains in its lower part a control loop for negative feedback, which in humans together with passive joint stiffness and damping from muscular-skeletal tissue yields a servo control (not shown in Fig. 1). With appropriate parameter adjustments of the servo, the actual movement corresponds to the desired movement defined by a set point signal (voluntary pose or displacement trajectory). This applies only in the absence of external disturbances. External disturbances need to be estimated and compensated, which is done on the basis of sensory inputs.

The external disturbances having impact on the robot during balancing can be assigned to one of four classes: (1) Support surface tilt, (2) support surface translation, (3) contact forces such as a push against or pull on the body, and (4) field forces such as gravity. The sensor inputs in the here considered experimental condition (eyes closed standing balance) are (a) proprioceptive sensation of the ankle joint angle and (b) angular velocity, (c) proprioceptive sensation of ankle torque, (d) a vestibular sensation of the head in space orientation with respect to the gravitational vertical (*space vertical*, SV), (e) head rotation velocity, and (f) head translational acceleration. The disturbance estimations are derived from these sensory inputs through sensor fusions and comprise in addition a detection threshold and a gain factor.

Figure 2 gives the conventions of the DIP used for the model. Note that physical variables are presented in upper case letters and their sensor-derived internal representations in the model as lower case letters. Signal fusions follow a summation semantics: trunk-space angle results from combining additively head-space and trunk-head angles, $\alpha_{ts} = \alpha_{hs} + \alpha_{th}$ (invalid combinations would be $\alpha_{hs} - \alpha_{th}$ or $\alpha_{hs} + \alpha_{tl}$). This applies for the disturbances estimations as well as for the sensory couplings between the hip with the ankle control module. Note the simplified notation of angles and angular velocity in the model of Fig. 1 as compared to Fig. 2.

The disturbance estimates command the servo to compensate the disturbances. This addition of a loop overall increases the loop gain, which generally tends to be slightly above the minimum for balancing. The increase occurs only during and to the extent of the external disturbance. The four estimation and compensation loops are taken to represent in humans long latency pathways via higher brain centers (basal ganglia, cerebral cortex). In Fig.1, the three upper disturbance estimators in the modules are viewed as producing torque signals. For feedback, these signals are

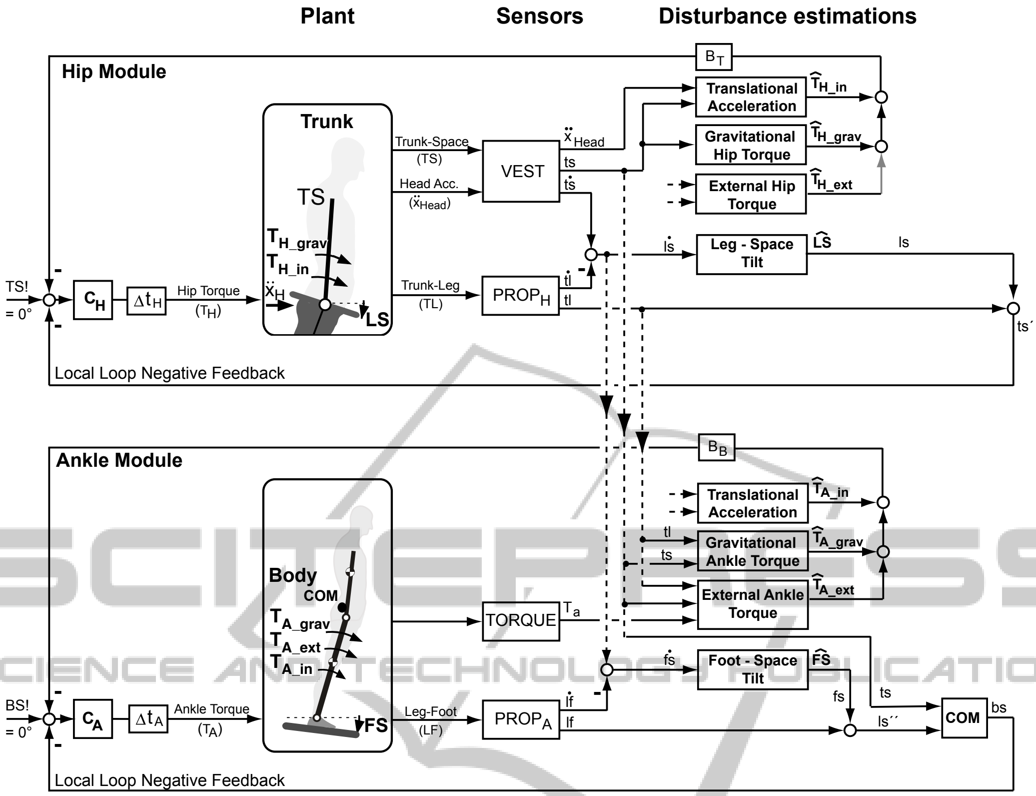

Figure 1: Schematics of the DEC model for DIP robot Posture control.

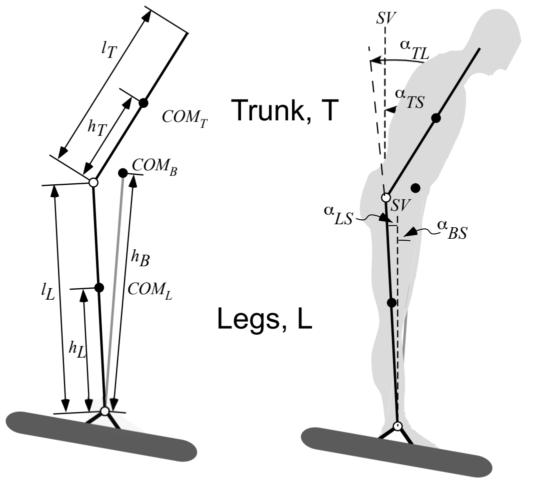

Figure 2: Conventions of the DIP posture parameters. SV, space vertical.

transformed into joint angle equivalents (boxes B_T and B_B). The Local Loops represent short latency loops through spinal cord and brain stem. Compensation of inter-link coupling forces tend to be covered by the estimators. Trunk angular acceleration exerts a coupling force on the leg link, which the ankle control module treats as a contact force disturbance. Leg angular accelerations produce eccentric rotation of the hip, which the hip control module treats as disturbances in terms of support surface translational acceleration and tilt.

The next subsections present the estimation models that are used for the DIP humanoid, referring to conventions defined in Figure 2.

2.1 Estimation of Leg-space Tilt

In the hip module of Fig. 2, the leg-space angle represents the support surface tilt disturbance for the trunk. The leg-space angle is estimated using the vestibular trunk-space angular velocity signal, $\dot{\alpha}_{ts}$ and a proprioceptive trunk-leg angular velocity signal, $\dot{\alpha}_{tl}$ in the following form:

$$\hat{\alpha}_{ls} = \int (\dot{\alpha}_{ts} - \dot{\alpha}_{tl})dt \quad (1)$$

The final estimate involves a velocity detection threshold and a gain factor, both of which were identified in human experiments (applies also to following estimates).

2.2 Estimation of Foot-space Tilt

In the ankle module, this estimate is obtained from the vestibular trunk-space angular velocity signal, $\dot{\alpha}_{ts}$ (down channeled from leg segment), the proprioceptive trunk-leg angular velocity signal, $\dot{\alpha}_{tl}$ and the leg-foot velocity signal, $\dot{\alpha}_{lf}$ as follows:

$$\hat{\alpha}_{fs} = \int \left(\dot{\alpha}_{ts} - \dot{\alpha}_{tl} - \dot{\alpha}_{lf}\right) dt \qquad (2)$$

2.3 Estimation of Support Translation

The vestibular sensor provides an estimate of trunk support translation acceleration as follows:

$$\hat{\ddot{x}}_H = \ddot{x}_{Vx} - \frac{d\dot{\alpha}_{ts}}{dt} l_T \qquad (3)$$

where $\ddot{x}_{Vx}$ is a horizontal head (vestibular) translational acceleration, $\ddot{\alpha}_{ts}$ is the head angular acceleration and l_T represents the distance between the vestibular organ and the hip joint. The $\ddot{x}_H$ estimate is used to estimate the hip torque as follows:

$$\hat{T}_{H_{in}} = \ddot{x}_H m_T h_T \qquad (4)$$

2.4 Estimation of Gravitational Torque

The estimation of the gravitational ankle torque is computed as:

$$\hat{T}_{A_{grav}} = m_B h_B g \alpha_{bs} \qquad (5)$$

The signal is processed in two parallel pathways, one via a low pass filter and gain factor to account for human data at low tilt frequencies, and the other with detection threshold and gain factor.

The estimation of the gravitational hip torque is computed in a corresponding way as:

$$\hat{T}_{H_{grav}} = m_T h_T g \alpha_{ts} \qquad (6)$$

2.5 Estimate of Contact Force

An external ankle torque from a push against the body is computed from a sensory signal of the active ankle torque ,T_a, and an internal estimate of the total torque, T_A which is obtained from the body-space angular acceleration as follows:

$$T_A = J_B \ddot{\alpha}_{bs} \qquad (7)$$

where the J_B is the moment of inertia of the body around the ankle joint. The external ankle torque is computed as:

$$\hat{T}_{A_{ext}} = T_A - T_{A_{grav}} - T_a \qquad (8)$$

The external hip torque can be computed in a corresponding way.

2.6 Estimation of Body-space Angle

Compensating in the ankle joint module the body COM requires its computation (Fig.2, box COM and inside box Gravitational Ankle Torque). Body-space position $\hat{\alpha_{bs}}$ is computed as:

$$\hat{\alpha}_{bs} = \frac{(h_T \alpha_{ts} + l_L \alpha_{ls}) m_T + h_T \alpha_{ls} m_L}{h_B m_B} \qquad (9)$$

where m_B is body mass, m_T is trunk mass, m_L is the mass of both legs, h_B is body COM height, h_T is trunk COM height, h_L is leg COM height and l_L is leg length. Assuming small angular changes, h_B is set constant.

3 EXPERIMENTAL SETUP

PostuRob II (Fig. 3) was constructed with human-like anthropometric parameters (Hettich et al., 2014). It consists of trunk, leg and feet segments of aluminum, interconnected by hinge joints representing the hip joints and the ankle joints. Signals from mechatronic sensors (vestibular, joint torque, joint angular position and velocity) were input into a real time PC, where the control model was executed as a compiled Simulink model (Real-Time Windows Target, The MathWorks Inc., Natick, USA). The vestibular

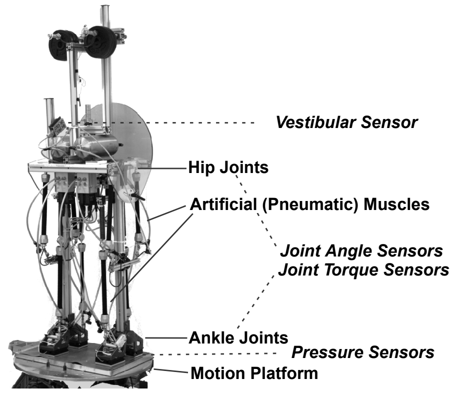

Figure 3: PostuRob II standing on a motion platform.

sensor processed accelerometer and gyrometer signals and delivered the signals (i)trunk angular velocity, (ii)trunk angle with respect to the gravitational vertical, and (iii)linear acceleration of the upper trunk end representing the head (Mergner et al., 2009). The torque commands for hip and ankle joints actuate artificial pneumatic muscles (FESTO, Esslingen, Germany). An inner torque control loop ensured that the actual torque matched the desired torque. Experiments were performed in a human posture control laboratory. External disturbances consisted of support surface tilt in the sagittal plane while the robot was standing on a 6 DOF motion platform. Furthermore, contact force stimuli were applied by pushes with the hand, and 4° voluntary lean of the trunk was commanded via the TS! set point signal (Fig.1) using a smoothed ramp. Estimated lumped time delays of the hip and ankle modules were set to 50 ms and 80 ms, respectively. Together with an estimated time delay of 40 ms for the PC processing, the delays amounted to 90 ms for the hip joint control and 120 ms for the ankle joint control.

4 RESULTS

Figure 4 shows in the first part the results obtained with a series of sinusoidal support surface tilts alone. Panel A gives the evoked kinematic sway responses, where α_{fs} reflects essentially the tilt stimulus and α_{BS} the body COM balancing response in the ankle joints. The other two traces are the trunk-space and leg-space angular excursions. Panels B and C give the sensed ankle torque and hip torque, respectively. The applied surface support tilt was of $\pm 4°$ amplitude and $0.1 Hz$.

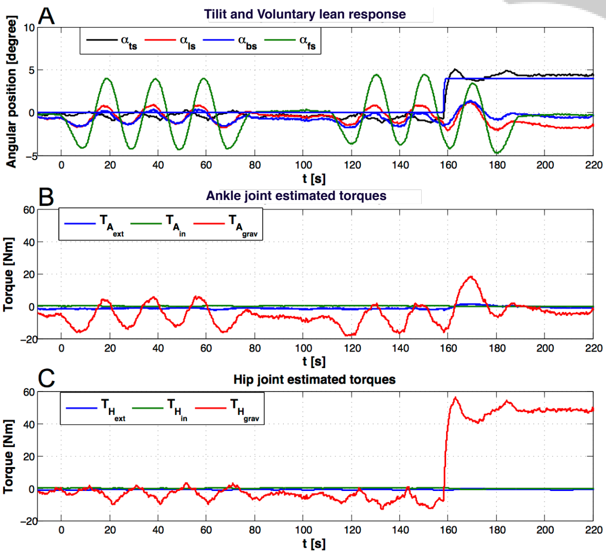

Figure 4: Superposition of support surface tilt and voluntary lean. Kinematic responses (A), sensed torque at the ankle joint (B) and the hip joint (C).

In the later part of Fig. 4, starting at about 110 s, a second tilt series starts. At around 160 s, a voluntary trunk lean of 4 degree forward is superimposed (see black trace). The DEC module of the hip joint brings the α_{ts} in the desired position, while the DEC module of the ankle joint continues with the α_{bs} balancing. The forward trunk lean is associated with backward leg lean in α_{ls} (red trace). It is mainly this inter-link coordination that limits the α_{bs} excursion, keeping the COM above the base of support. This hip-ankle coordination is human-like (Hettich et al., 2014).

Figure 5 shows the results obtained in PostuRob II when superimposing external push stimuli and support surface tilt (presentation as in Fig. 4). Four push stimuli (large transients) were applied, one of them during a support surface tilt series (sine-like curves). Thus, the robot's stance stabilization by the DEC controller tolerates the superposition of the two external disturbances.

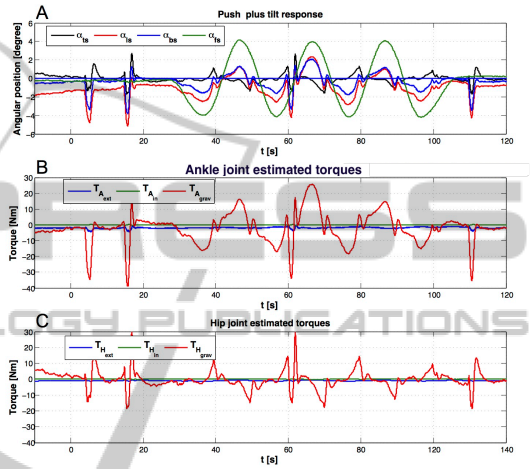

Figure 5: Push responses: A) Angular position responses, B) and C) are the sensed torques for the ankle and hip, respectively.

5 CONCLUSIONS AND FUTURE WORK

The experiments show that the DEC controller in the DIP robot is able to deal with superposition of more than one type of external disturbances and superposition of external disturbances and voluntary movements such a trunk lean. The experiments also demonstrate that the controller is tolerant against spontaneous body sway originating from internal noise, mostly from vestibular input, this during the balancing of external disturbances and in the presence of a lasting trunk lean that challenged the balancing. Furthermore, the robot demonstrated a human-like mechanical compliance, which was particularly evident in its reactions to the external push.

The experiments also revealed emergence of a hip-ankle coordination during voluntary trunk lean, which on closer inspection also occurred in the responses to external disturbances, and is human-like (Alexandrov et al., 1998; Freitas et al., 2006). It is related to the ankle controller's task to stabilize the body COM over the base of support (it is not found when the task is to maintain the leg-space orientation vertical). Noticeably, the coordination occurs here through the interactions between the hip and ankle control modules rather than through preprogrammed motor command patterns, which also have been used to control robots in the form of synergies (Hauser et al., 2011).

Currently, further developments of the DEC concept comprise tests in different robotics platforms. Furthermore, under investigation are generalizations of the modular structure of the DEC controller to conditions that are not a multiple inverted pendulum. This includes controlling balance in the frontal plane, alone and in combination with the sagittal plane balancing, generic poses with high degrees of freedom, and integrating the balancing in the control of gait. In particular, in the framework of the H_2R project (see below), the controller is tested for the balancing control of a robot with multiple DOFs with compliant actuation, developed within the consortium, and integrated in the gait controller for the stabilization of some links. In the framework of the EMBalance project, the DEC controller is modified such that the robot's balancing behavior mimics certain neurological deficits such as bilateral vestibular damage or loss.

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REFERENCES

Alexandrov, A., Frolov, A., and Massion, J. (1998). Axial synergies during human upper trunk bending. *Experimental Brain Research*, 118(2):210–220.

Bastian, A. J. (1997). Mechanisms of ataxia. *Physical Therapy*, 77:672–675.

Cheng, G., Hyon, S.-H., Morimoto, J., Ude, A., Hale, J. G., Colvin, G., Scroggin, W., and Jacobsen, S. C. (2007). CB: A humanoid research platform for exploring neuroscience. *Advanced Robotics*, 21:1097–1114.

Cnyrim, C., Mergner, T., and Maurer, C. (2009). Potential role of force cues in human stance control. *Experimental Brain Research*, 194:419433.

Freitas, S. M., Duarte, M., and Latash, M. L. (2006). Two kinematic synergies in voluntary whole-body movements during standing. *Journal of Neurophysiology*, 95(2):636–645.

Goswami, A. (1999). Postural stability of biped robots and the foot-rotation indicator (FRI) point. *The International Journal of Robotics Research*, 18(6):523–533.

Hauser, H., Neumann, G., Ijspeert, A. J., and Maass, W. (2011). Biologically inspired kinematic synergies enable linear balance control of a humanoid robot. *Biological cybernetics*, 104(4-5):235–249.

Hettich, G., Asslnder, L., Gollhofer, A., and Mergner, T. (2014). Human hipankle coordination emerging from multisensory feedback control. *Human Movement Science*, 37:123–146.

Kuo, A. D. (2005). An optimal state estimation model of sensory integration in human postural balance. *Journal of Neural Engineering*, 2(3):S235.

Lippi, V., Mergner, T., and Hettich, G. (2013). A bio-inspired modular system for humanoid posture control. . *In: Ugur, E., Oztop, E., Morimoto, J., and Ishii, S. (Eds) Proceedings of IROS 2013 Workshop on Neuroscience and Robotics "Towards a robot-enabled, neuroscience-guided healthy society"*.

Maurer, C., Mergner, T., and Peterka, R. J. (2006). Multisensory control of human upright stance. *Experimental Brain Research*, 171:231250.

Mergner, T. (2010). A neurological view on reactive human stance control. *Annual Review Control*, 34:77198.

Mergner, T., Huethe, F., Maurer, C., and Ament, C. (2006). Human equilibrium control principles implemented into a biped robot. *Robot Design, Dynamics, and Control*, 487:271–279.

Mergner, T., Maurer, C., and Peterka, R. J. (2003). A multisensory posture control model of human upright stance. *Progress in Brain Research*, 142:189–201.

Mergner, T., Schweigart, G., and Fennell, L. (2009). Vestibular humanoid postural control. *Journal of Physiology - Paris*, 103:178–194.

Nori, F., Peters, J., Padois, V., Babic, J., Mistry, M., Ivaldi, S., et al. (2014). Whole-body motion in humans and humanoids. In *Workshop on New Research Frontiers for Intelligent Autonomous Systems*.

Peterka, R. J. (2002). Sensorimotor integration in human postural control. *Journal of Neurophysiology*, 88:10971118.

Schweigart, G. and Mergner, T. (2008). Human stance control beyond steady state response and inverted pendulum simplification. *Experimental Brain Research*, 185:635–653.

Torricelli, D., Mizanoor, R. S., Gonzalez, J., Lippi, V., Hettich, G., Asslaender, L., Weckx, M., Vanderborght, B., Dosen, S., Sartori, M., et al. (2014). Benchmarking human-like posture and locomotion of humanoid robots: A preliminary scheme. In *Biomimetic and Biohybrid Systems*, pages 320–331. Springer.

van der Kooij, H., Jacobs, R., Koopman, B., and Grootenboer, H. (1999). A multisensory integration model of human stance control. *Biological Cybernetics*, 80:299–308.