CENTRAL NERVOUS SYSTEM DEMAND ON HUMAN ERECT POSTURE CONTROL: AN OPEN AND CLOSED LOOP MODEL

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Abstract. *The posture control system is highly complex, involving multiple sensory systems and motor components. The necessary demand to stabilize the human posture is associated with the way Central Nervous System controls and keeps the quiet erect posture. In existing posture control models, a continuous variation of final element control signal is observed, which will certainly wear the controller. A solution to preserve it would be the increase in commutation period, causing final element of control to act only when postural balance is distantly related to reference signal. A way to implement this solution is to use controllers which have a differential gap about the reference signal, defined by a superior and inferior limit. A simple pendulum model is used to represent the dynamics of the human musculoskeletal system on sagittal plane, with neural control system sending instructions in order to produce a corrective torque that resists body position deviation. A system disturbance is obtained by the insertion of a noise with adequate amplitude gaussian distribution, reproducing the environmental factors which interact with human beings. A feedback control model was carried out, which reference position deviation is perceived and corrected by a Proportional-Integral-Derivative controller, that resembles neuromuscular parameters, added to passive viscous-elastic properties of the muscle. A model for superior and inferior limits up to 0.5 of reference signal was simulated. In this gap the system acted as an open loop, therefore without the correction of reference signal. It was observed that the option of controller with differential gap worsens the quality of control, but demands less the final element of control. Inasmuch as the physiological characteristics of posture balance oscillation were reproduced, the option with differential gap is reasonable since the final element of control is saved.*

Keywords*: biomechanics, postural control, inverted pendulum, differential gap, feedback. , zona morta, feedback.*

1. INTRODUCTION

The postural control is an arrangement control of body segments based on sensory information from different sources, including a body position control in space, aiming for stability and orientation (Shumway-Cook and Woollacott 2001).). In order to achieve balance adjustment, postural control system needs pieces of information on relative positions of body segments and the magnitude of forces acting on the body. In order to establish a vertical orientation, multiple sensory references are used, such as gravity (vestibular system), supporting surface (somatosensitive system) and the relation between our body and the existing objects in space (visual system) (Horstmann and Dietz 1990; Rothwell 1994; Winter 1995; McCollum, Shupert et al. 1996).

There was a significant progress on comprehension of human postural control, but this control system is not totally understood. Recently, based on important empirical discoveries, some researchers proposed different control ways which challenged classic theories of postural control system (Collins and De Luca 1993; Winter, Patla et al. 1998; Gatev, Thomas et al. 1999; Peterka 2000; Winter, Patla et al. 2001; Morasso and Sanguineti 2002; Winter, Patla et al. 2003). In their experiments, (Baratto, Morasso et al. 2002) conclude that muscular stiffness cannot be regulated by a neural way, which contradicts (Winter, Patla et al. 1998; Carpenter, Frank et al. 1999; Loram and Lakie 2002). There are many questions to be resolved about both muscular properties (Winter, Patla et al. 1990; Winter, Patla et al. 1998; Gatev, Thomas et al. 1999; Morasso, Baratto et al. 1999; Morasso and Schieppati 1999; Winter, Patla et al. 2001; Morasso and Sanguineti 2002; Winter, Patla et al. 2003), and the Central Nervous System demand, such as the participation of sensory systems (Winter 1995; Loram and Lakie 2002) in stabilizing the human postural balance. There are still controversies related to the type of selected control. Pieces of evidence suggest that posture is stabilized by anticipatory control in cooperation with elastic properties of muscle. These new models and theories were not yet totally tested and assimilated. They present conflicting aspects among themselves and this discussion is still quite active in scientific community. Therefore there are a lot of questions to be resolved, such as the participation of Central Nervous System in postural control, what muscular property values assure system stabilization.

The postural control system is highly complex, involving multiple sensory systems and motor components. In the existing postural control models, it is observed that there is a continuous variation of final element control signal, which will certainly wear the controller. A solution to preserve it would be the increase in commutation period, causing final element of control to act only when postural balance is distantly related to reference signal. A way to implement this solution is to use controllers which have a differential gap about the reference signal, defined by a superior and inferior limit.

2. MÉTODOS

2.1. Model Description

A simple postural control model was assumed, according to Figure 1, with all input and output restricted to sagittal plane (anteroposterior direction). The neural control system perceives a deviation of postural balance related to a reference posture and sends a command to produce corrective torque in order to resist body position deviation in erect posture.

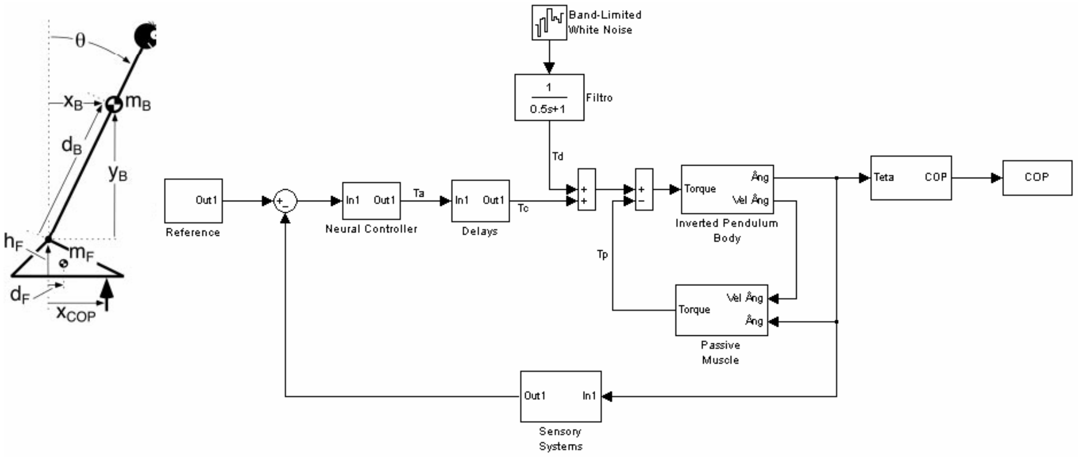

Figure 1. Human postural control feedback model during erect posture.

A simple pendulum model is used to represent the dynamics of human musculoskeletal system on sagittal plane in a quite simplified way in order to present the basic concepts of Physical-Mathematical modeling. Considering a body on sagittal plane represented by two rigid segments, the feet and the rest of the body, the feet are steady on the ground and the rest of the body behaves as a rigid segment articulated in foot by hinge type articulation, ruled by Eq.(1).

$$M + m \cdot g \cdot d \cdot sen\alpha = I \frac{d^2\alpha}{dt^2} \tag{1}$$

Where *I* is the moment of body inertia around the ankle articulation and *m* is a mass of the body. The variables *I*, *d* and *m* are constant and given by the anthropometric scale of (Fukuoka, Tanaka et al. 1999) and (Patton 1998). The input signal is the torque in ankle articulation, consisting of three components.

Equation (2) presents the fundamental relation between COP and GL positions in relation to *Fx*: the difference COP-GL is negatively correlated with *Fx* and when *Fx* is null, COP and GL coincide.

$$COP - GL = -\left(\frac{I}{m \cdot d} + h\right)\frac{Fx}{mg} \tag{2}$$

A perturbation (T_d) is a random torque disturbance, which contributes to produce a postural balance. An adequate understanding of postural balance is obtained when the nature of disturbance is identified. One of the scientific community questions on quiet erect posture is about what intrinsic disturbance occurs when people remain steady. Not considering any voluntary disturbance caused by an external factor and which is not predictable, we are exposed to innumerable disturbances that we don't know its causes and how it destabilizes posture. There are possible causes that occasion the oscillation, such as physiologic noise, physiologic factors (fatigue, venous return), mechanical instability, facilitation of control mechanisms besides exploratory factors (including interactions with the environment). When we breathe, there is a slight body balance that must be equivalent to corrective forces in order to avoid the lack of equilibrium. Milkowski and collaborators (2004), in their experiments, measure the postural balance disturbance calculated for three breathing conditions (relaxed, regular and after the exercise). Their considerations give an account that breathing is the major component which destabilizes erect posture. Many other disturbances, intrinsic to the body, contribute to its postural balance. Conforto and collaborators (1993) have answered some of the searches if the disturbance attributed to hemodynamics is relevant to postural balance. The inherent postural balance disturbances are not all known, but the order of magnitude attributed to these disturbances are.

Another component is the control torque (T_c) that corrects torque disturbance and the action of gravity on body. Such component is equal to neural controller action, with the output of Proportional-Integral-Derivative controller (PID) added to a differential gap from deviation corrections of human body position in relation to a reference. So it was assumed that sensory systems provide an accurate measure of postural balance value, not adding any dynamics to the system. The neural controller is specified by three constants K_p, K_d and K_I, that are respectively proportional to reference position deviation, reference velocity and the integral in time of reference value error.

The third component is equivalent to passive muscular parameters, considering its viscous-elastic properties, as passive stiffness (K_{pas}) and passive viscosity (B_{pas}). In this case, the corrective torque is the summation of neural torque and passive torque, determined by intrinsic properties of stiffness and viscosity of the ankle.

The implemented controller presents a commutation period, causing final element of control (neural controller action) to remain on and off during a period of time. A way to implement this solution is to make use of controllers that have a differential gap about the reference value, defined by a superior limit (sup) and an inferior limit (inf). In differential gap the controller output presents a null value, which means there is no reference value error signal correction. Thus, the model presents equivalent characteristics to an open loop system and the Central Nervous System, represented by PID controller, is not acting in maintaining the postural balance. A model for superior and inferior limits up to 0.5° of reference signal was simulated.

2.1. Model Simulation

All simulations were run by Simulink software, version 6.3 Matlab 7.1 (The MathWorks Inc., Natick, Mass., USA). The duration of simulation equals 100 seconds, with simulation parameters fix point of 0.001 s and resolution algorithm of differential equations associated with Dormand-Prince model (ode5).

A 'band-limited white noise' Matlab block was run as noise source, with noise power of 6.4 and time sample of 0.4 s, applied with first order low-pass filter with a constant of time 0.5 s and unitary gain. Such noise source equals an intrinsic disturbance when people remain steady (Hunter and Kearney 1981; Conforto, Schmid et al. 2001).

The reference angle for the ankle was 0°. For this angle, the PID controller gain factors were simulated for a variation from 200.0 to 1000.0 Nm • rad^{-1}, with gaps of 10.0 Nm • rad^{-1}, for proportional gain associated with a variation from 20.0 to 100.0 Nm • s • rad^{-1}, with gaps of 1,0 Nm • s • rad^{-1}, Such combination produced 80.80 = 7200 simulations for each differential gap. Since the differential gap was varied up to 0.5°, the whole of simulations was 7200. 6 = 43200 simulations. The integral gain equals 0 Nm • s^{-1} • rad^{-1}.

The passive muscular properties are equivalent to viscous-elastic components, with passive stiffness of 64% of critical stiffness, equals body mass multiplied by its height and gravity (Conforto, Schmid et al. 2001), which produces the value of 504.8 Nm • rad^{-1} and passive viscosity of 175.0 Nm • s • rad^{-1} (Casadio, Morasso et al. 2005).

The total delay of system is equivalent to the delay of sensory systems of 0.100 s (Maurer and Peterka 2005), added to the transmission delay of neural signal and the electromechanical delay of muscle both of 0.050s, which produces a value of 0.200s.

The first five second gap will be considered as an adaptation period and will not be examined. The analysis of data into the domain of time consists in calculus of the mean, the standard deviation, instantaneous speed and the average speed, root mean square (RMS) and RMS of speed, jerk (Patton 1998) of signal of COM and COP.

3. RESULTS AND DISCUSSION

Figure 2 shows the amplitude results of COP for variations of proportional and derivative gain without differential gap. A simple model by feedback of postural control system, without the introduction of differential gap, is capable of reproducing experimental results of postural balance. Such simulations show that the displacement of COP obtained by computer models can resemble experimental variations by an appropriate school of human postural control model parameters. A stability zone for values of proportional gain is observed from 400 to 600 Nm/rad. In such range the postural balance characteristics are similar to experimental results, which are consistent with recent results (Bottaro, Casadio et al. 2005; Maurer and Peterka 2005). However, this model does not estimate the Central Nervous System strategy for erect posture control proposed by this article.

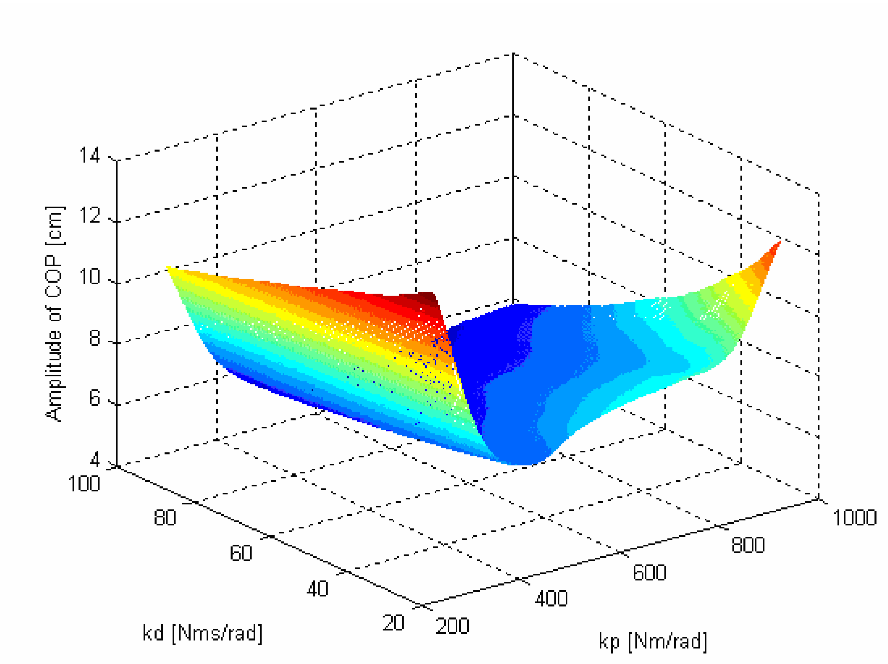

Figure 2. Amplitude of COP for parameter variations of PID controller for a model without differential gap.

When a value of differential gap with superior and inferior limits equal 0.2° is used, a similarity in characteristics of amplitude curve of COP is observed for variations of proportional and derivative gain when compared to a system without differential gap. These characteristics are also reproduced in other statistics properties of postural balance as the speed of COP. The stability zone for values of proportional gain from 400 to 600 Nm/rad is observed, not presenting a significant increase in signal characteristics of COP compared to models without differential gap.

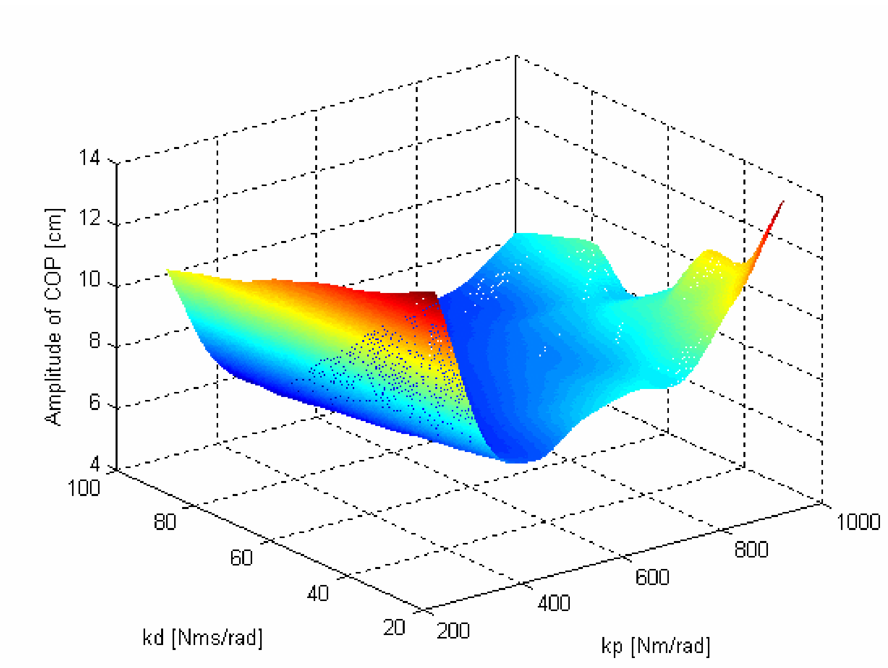

Figure 3. Amplitude of COP for parameter variations of PID controller for a model with differential gap for superior and inferior limits equal 0.2°.

However, Figure 4 shows, in percentage terms, the period which the value of ankle angle was within the superior and inferior limits of differential gap equal 0.2°, thus in open loop and with controller gain equals zero. For the found stability zone, approximately 35% of system continued to act in open loop, not asking for a Central Nervous System demand in posture maintenance.

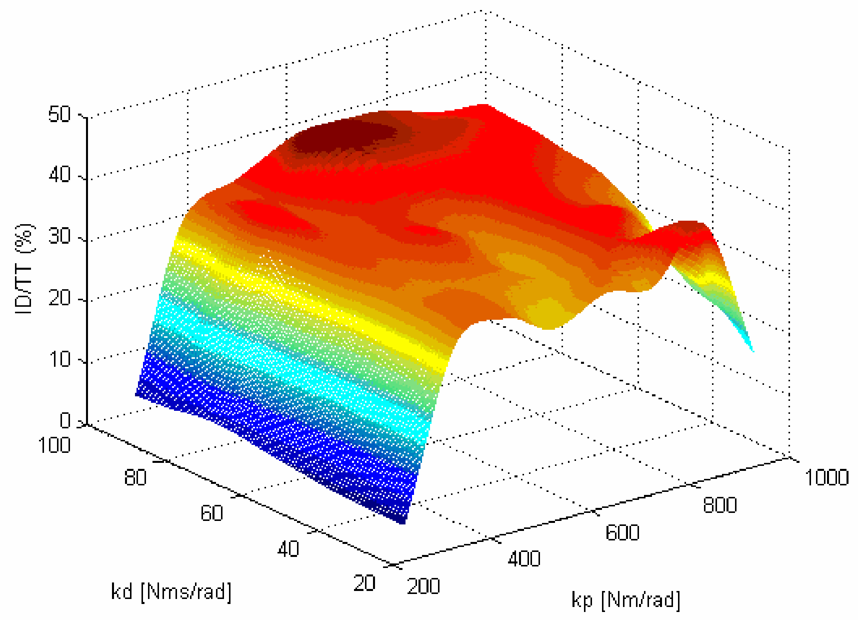

Figure 4. Percentage which the signal of ankle angle was within the superior and inferior limits of differential gap equal 0.2°.

When the superior and inferior limits of differential gap change into a value of 0.4°, the amplitude of COP increases, keeping similar characteristics in relation to the previous ones. Nevertheless, the percentage of time the value of ankle angle is within the differential gap increases.

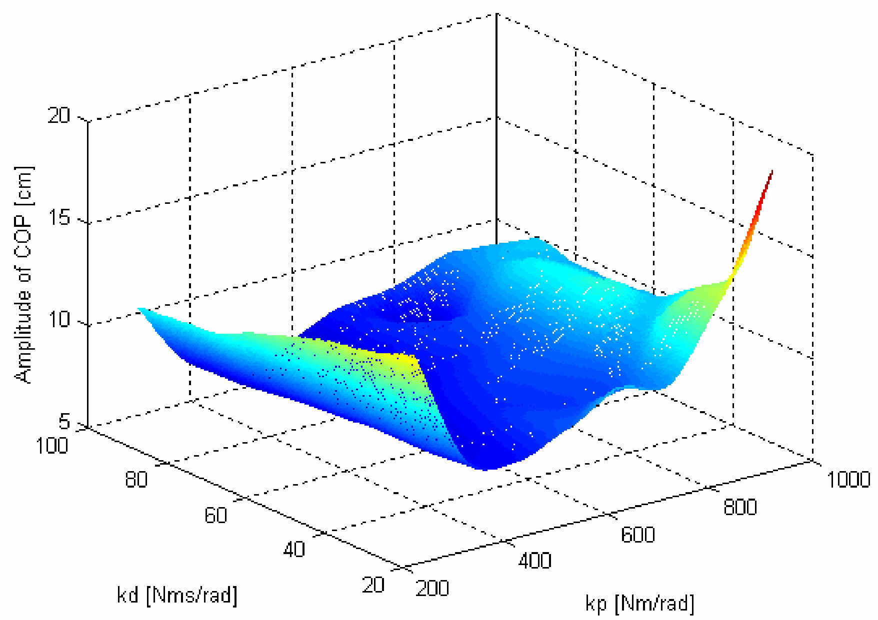

Figure 5. Amplitude of COP for parameter variations of PID controller for a model with differential gap for superior and inferior limits equal 0.2°.

Tal região de estabilidade ainda é encontrada, aumentando aproximadamente a amplitude do COP de 6 cm para 8 cm quando comparado a um modelo com o controlador sem intervalo diferencial. Tal aumento é compensado por um significativo aumento da percentagem do período em que o valor do ângulo do tornozelo se manteve dentro dos limites superior e inferior do intervalo diferencial iguais a 0,4º, refletindo em uma diminuição da demanda do SNC e a atuação do sistema equivalendo a uma malha aberta.

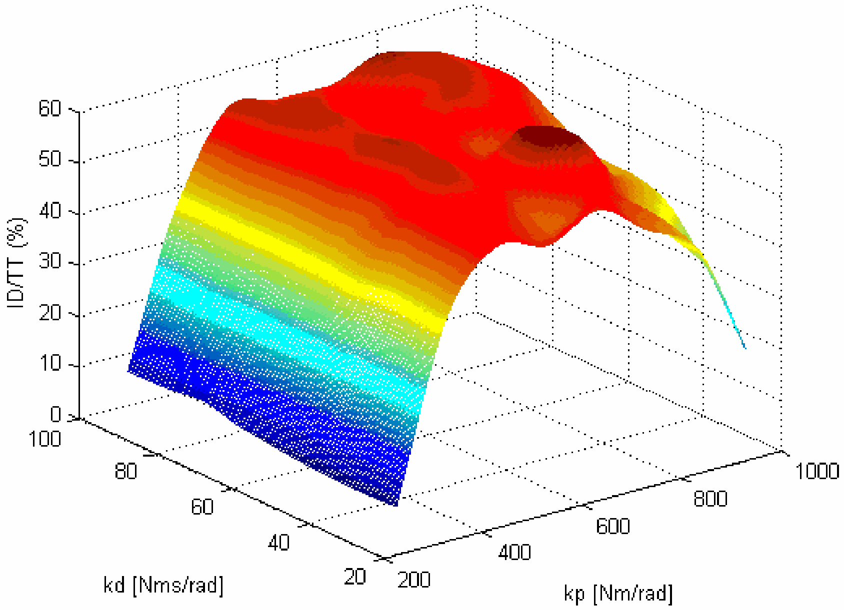

Figure 6. Percentage which the signal of ankle angle was within the superior and inferior limits of differential gap equal 0.2°.

4. CONCLUSION

The amplitude of oscillations without damping is bigger in the case of the controller with gap. On the other hand, it is observed that the final element of control will be less requested for it will be commuted in bigger gaps. Therefore, in performed computer simulations, the option of controller with differential gap worsens the quality of control but requests less the final element of control. If the controlled variable is acceptable, besides the oscillation moves longer away from its reference value than that one without differential gap, the option with differential gap will be reasonable for saving the final element of control. A proposal to minimize the characteristics of temporal signal of COP such as amplitude, RMS and velocity, for future work, is to control three zones, with a control which the controller output normally acts according to its control algorithm for values of controlled variable out of a specific zone. Within this zone the controller output is constant in a specific value. The proposed model is very simple and able to reproduce the statistics properties of postural balance revealed by experimental results. It provides the Central Nervous System demand for the maintenance of postural control.

5. ACKNOWLEDGEMENTS

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