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A new measure for upright stability

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ABSTRACT

The control of balance is a primary objective in most human movements. In many cases, research or practice, it is essential to quantitatively know how good the balance is at a body posture or at every moment during a task. In this paper we suggest a new measure for postural upright stability which assigns a value to a body state based on the probability of avoiding a fall initiation from that state. The balance recovery problem is solved for a population sample using a strength database, and the probability of successfully maintaining the balance is found over the population and called the probability of recovery (PoR). It, therefore, describes an attribute of a body state: how possible the control of balance is, or how safe being at that state is. We also show the PoR calculated for a 3-link body model for all states on a plane, compare it to that found using a 2-link model, and compare it to a conventional metric: the margin of stability (MoS). It is shown, for example, that MoS may be very low at a state from which most of the people will be able to easily control their balance.

1. Introduction

A primary objective in many human movements is the control of balance. Balance gets disturbed by perturbations of different types, then, escaping from the initiation of a fall the individual starts a procedure to recover balance. No matter what the perturbation source is, after a person feels at risk of the loss of balance and after some reaction delay, the recovery procedure commences and lasts until advancing the posture to a safe one. Let us call the start point of the recovery trial a "*perturbed state*", and without loss of generality, assume that the objective of recovery is to drive the posture to an exactly upright position without any part of the body moving. The balance is *recovered* if and only if this objective is achieved. The possibility of an individual to recover his or her balance from a perturbed state, in addition to the individual's characteristics, depends on the perturbed state. The more severe a perturbation is, the more recovering from the corresponding perturbed state becomes difficult, where one may say that state is far from balance, or the *postural upright stability* at that state is poor. A quantitative metric to assess the upright stability at a certain state is the matter of interest in this work.

Traditionally, the vertical projection of the center of mass (CoM) was supposed to be within the base of support (BoS) for the balance to be maintained, and its shortest distance to the edge of BoS was used to show how far from the balance a state is (Borelli, 1989; Dyson, 1977; Kuo, 1995; Patla et al., 1990; Shumway-Cook and Woolacott, 1995; Winter, 1995a). BoS is the area which transfers the body weight to the ground, i.e. the possible range of the center of pressure (CoP). Later, it has been brought to attention that this criterion is neither sufficient nor necessary in dynamic situations, and the velocity of the CoM should also be accounted for (Pai and Patton, 1997; Iqbal and Pai, 2000). They obtained a feasible stability region in the position–velocity plane, which was reformulated later by Hof et al. (2005) as: the condition for dynamic stability is being the "XcoM" within the BoS. XcoM is the "*position of the extrapolated CoM*" which is a linear combination of the horizontal position of CoM and its time derivative. They also suggested a new measure for stability of a body state, the margin of stability (MoS), as the shortest distance of XcoM to the edge of BoS. However, MoS is not well related to the "possibility" of maintaining the balance or "safety" at a state. It may be very small for a state while it is highly safe. The reverse is also true: high MoS is not necessarily highly stable.

A method has been developed to calculate the risk of fall initiation at a given position and velocity of the CoM (Honarvar and Nakashima, in press), which works only for a simple mechanical model. This paper takes advantage of the idea of the fall initiation risk and suggests a new measure for the postural upright stability. A value between 0 (highly unstable) and 1 (highly stable) is allocated to a body state describing how possible maintaining/regaining the balance is at that state. It is in close relation with how safe being in a certain state is, with respect to the loss of

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balance. It will be defined conceptually first, then a mechanical model will be selected as a platform based on which we will explain how it may be calculated and show some results. Results will be shown and compared for a 2-link model as well. This new measure will also be compared to the MoS. Finally the main limitations of this work will be discussed.

2. Methods

2.1. Conceptual definition

The term "state" will be used in this paper to describe the body situation at a moment which may be expressed by a vector consisting of all postural and movement variables, e.g., joint angles and angular velocities. State space is then a virtual n-dimensional space (n: the number of state variables), each axis of which is one of the joint angles or angular velocities. Any human movement, like balance recovery trial, may be described by a curve in the state space, showing what the body state is at any point in time.

Postural stability is different from state to state. At some body states (e.g., CoM behind the BoS with a backward velocity) no one is able to maintain its balance and a fall will surely initiate (low postural stability) while from some other states almost everyone is able to control its balance (high postural stability). A postural stability value should be assigned to every state to show how good the balance is at each state.

An individual at a perturbed state must make some effort to avoid initiation of a fall. Even under a perfect reaction, some subjects will be successful and the others will lose their balance, depending on their strength. The portion of fallers varies from state to state. One may argue that a bigger stability value should be granted to the state from which a smaller portion of the society will initiate a fall, which directly implies how safe that state is. Thus using the population's statistical characteristics and taking advantage of the concept of probability, the postural stability at a state may be defined as the probability of the balance to be recoverable from that state over the entire population, without initiation of a fall, and called the *probability of recovery* (PoR).

PoR, may be solved on any mechanical model, whether planar or spatial, paired legs or not, and any number of segments. Nevertheless the complexity of the model dramatically increases the computation burden. In order to define this new stability measure in more details and illustrate how it will be found for a state, a not so simple, yet not so complicated mechanical model was selected as a chassis in this paper, although the methodology may be extended to other mechanical models.

2.2. PoR for a 3-link mechanical model

2.2.1. Model

In this work we focus on non-stepping sagittal planar models capable only of anterior/posterior movements, in particular on a 3-link model consisting of feet, lower limbs excluding feet ("Legs"), and the upper body (head, arms, and trunk; "HAT"), jointed at the ankle and hip (Fig. 1). For a higher number of segments, the method is the same. The body state (X) at a moment may be expressed uniquely by a 4-variable set: Legs and HAT inclination angles and their angular velocities; $X = \begin{bmatrix} \theta_L & \theta_H & \dot{\theta}_L & \dot{\theta}_H \end{bmatrix}^T$. External forces are (1) gravitational force applied to the feet, Legs, and HAT at their CoMs, and (2) a ground reaction force (GRF) applied to the feet at the CoP. In order for the feet to remain stationary on the ground, (1) CoP must remain within the foot length, (2) the vertical component of GRF must be upward (pressure force), and (3) its horizontal component must meet the static friction requirements (the *foot constraints*). The control inputs into this model are ankle and hip torques, by which the individual controls his or her posture. Control inputs at state X are limited to a band $T_{\text{Set}}(X) = [T_{\text{PF}_{\text{Max}}}(X),\ \ T_{\text{DF}_{\text{Max}}}(X),\ \ T_{\text{HE}_{\text{Max}}}(X),$ $T_{\text{HF}_{\text{Max}}}(X)]$ which varies with the state, but $T_{\text{Set}}(0)$ is an attribute of the individual. PF, DF, HE, and HF stand for plantar flexion, dorsiflexion, hip extension, and hip flexion, respectively. For example, $T_{\text{PF}_{\text{Max}}}(0)$ is the maximum plantar flexion torque this specific person can apply on his or her ankle in a still, erect standing position. The dynamic equation for such a system may be expressed in the common form of $M(q)\ddot{q} = C(q,\dot{q}) + G(q) + u$, where q is the coordinate vector ($q = [\theta_L\ \theta_H]^T$), u is the control input vector, M, C, and G are inertial, Coriolis, and gravity terms.

2.2.2. The balance recovery problem

It is the problem of checking whether the control of balance at a given perturbed state X_0 is possible for a certain subject with a given $T_{\text{Set}}(0)$. With a control input trajectory (input at every point in time) candidate and a given initial state, a computer program may solve the dynamic equation (e.g., by Runge–Kutta method) and obtain the state trajectory $X(t)$. Control input trajectories will be searched on, and if there exists one such that (1) drives the body from X_0 to 0, (2) complies with the applicable input range at every state ($T_{\text{Set}}(X)$) for that specific subject, (3) all the joint angles remain within their range of motion, (4) foot constraints always hold, and (5) the movement excludes a fall, the outcome of the balance recovery problem is positive. Though several methods have been developed to find an optimal input trajectory for a movement (see e.g., Helbig et al., 1998; Atkeson and Stephens, 2007; Honarvarmahjoobin et al., 2009) a direct search over the possible input trajectories should be utilized since only the existence of a solution is important here.

2.2.3. Torque limits at a given state, $T_{\text{Set}}(X)$

Models have been generated to simulate the force–length–velocity dependency of muscles or torque–angle–angular velocity relationships for joints, based on a Hill-type model (Hill, 1938; Chow et al., 1999; King and Yeadon, 2002; Anderson et al., 2007). This study used the model developed by Anderson et al. (2007) which suggests Eq. (1) to correlate the passive torque (T_{ps}) to the joint angle (θ), and Eq. (2) to correlate the maximum active torque (T_{ac}) to the joint angle and angular velocity ($\dot{\theta}$)

$$T_{ps}(\theta) = B_1 e^{k_1\theta} + B_2 e^{k_2\theta} \tag{1}$$

$$T_{ac}(\theta,\dot{\theta}) = \begin{cases} C_1\ \cos(C_2(\theta - C_3))\left(\frac{2C_4C_5 + \dot{\theta}(C_5 - 3C_4)}{2C_4C_5 + \dot{\theta}(2C_5 - 4C_4)}\right); & \dot{\theta} \ge 0 \\ C_1\ \cos(C_2(\theta - C_3))\left(\frac{2C_4C_5 - \dot{\theta}(C_5 - 3C_4)}{2C_4C_5 - \dot{\theta}(2C_5 - 4C_4)}\right)(1 - C_6\dot{\theta}); & \dot{\theta} < 0 \end{cases} \tag{2}$$

$$T(\theta,\dot{\theta}) = T_{ps}(\theta) + T_{ac}(\theta,\dot{\theta}) \tag{3}$$

where B_1, B_2, k_1, k_2, C_2, C_3, C_4, C_5, and C_6 and are correlation constants. Values obtained by Anderson et al. (2007) are given in Table 1. Constant C_1 equals to $T_{\text{jntmax}}(0)$; $\text{jnt} = \{\text{PF, DF, HE, HF}\}$ and $T = T_{\text{jnt}_{\text{max}}}(\theta_{\text{jnt}}, \dot{\theta}_{\text{joint}})$; $\text{jnt} = \{\text{PF, DF, HE, HF}\}$. For example, to find the maximum active ankle torque in the plantar flexion direction, when the ankle angle is θ_A and its velocity is $\dot{\theta}_A$, substitute $C_1 = T_{\text{PF}_{\text{Max}}}(0)$ in Eq. (2) (since $T_{ps}(0) \approx 0$) and find $T_{ac}(\theta_A, \dot{\theta}_A)$. This added to $T_{ps}(\theta_A)$ found by Eq. (1) delivers the maximum plantar flexor torque at $(\theta_A, \dot{\theta}_A)$.

2.2.4. Probability of recovery, $\text{PoR}(X_0)$

Values of $T_{\text{Set}}(0)$ for a population sample of 553 adults are available at National Institute of Technology and Evaluation (NITE), 2003. Average (SD) for $T_{\text{PF}_{\text{Max}}}(0)$, $T_{\text{DF}_{\text{Max}}}(0)$, $T_{\text{HE}_{\text{Max}}}(0)$, $T_{\text{HF}_{\text{Max}}}(0)$ are -91.65 (56.24) N m, $+47.66$ (14.58) N m, -87.85 (73.41) N m, and $+191.09$ (73.87) N m, respectively. Fig. 2 shows the distribution. For a given initial state X_0 a computer program solves the balance recovery problem for each subject (i.e., for each $T_{\text{Set}}(0)$ data), integrates the results and delivers which portion of them have the possibility of regaining their stability when released from X_0, which is, by definition, $\text{PoR}(X_0)$. PoR hence takes values between zero (0%, no one) and one (100%, everyone).

For the reference and later comparison, margin of stability as defined by Hof et al. (2005) is

$$\text{MoS} = \begin{cases} l_F - \text{XcoM} & ;\ \text{XcoM} \ge l_F/2 \\ \text{XcoM} & ;\ \text{XcoM} < l_F/2 \end{cases}$$

where $\text{XcoM} = x + v/\omega_0$, $\omega_0 = \sqrt{g/l_{B_{cm}}}$, $x = x_A - l_{B_{cm}}\ \sin\theta_B$, $v = dx/dt$. Positive MoS implies the feasible recovery

3. Results

3.1. 3-Link model

For the 3-link model (3LM) of Fig. 1 PoR may be calculated for every single point in the 4-dimensional state space ($X = [\theta_L, \theta_H, \dot{\theta}_L, \dot{\theta}_H] \in \mathbb{R}^4$). Here it is shown for states on a 2-dimensional subspace of equal legs and HAT angles, and equal velocities, i.e.,

$$\theta_L = \theta_H \quad \& \quad \theta_L = \theta_H \quad \text{at} \quad t = 0 \tag{4}$$

mapped on the $\hat{x} - \hat{v}$ plane, the axes of which are the horizontal displacement of CoM of the entire body (except feet) normalized to the foot length ($\hat{x}$), and its time derivative ($\hat{v}$)

$$\begin{aligned} \hat{x} &= -\frac{l_{L_{CM}}\ \sin(\theta_L)m_L + (l_{L_H}\ \sin(\theta_L) + l_{H_{CM}}\ \sin(\theta_H))m_H}{l_F(m_L + m_H)} \\ \hat{v} &= -\frac{l_{L_{CM}}\ \cos(\theta_L)\dot{\theta}_L m_L + (l_{L_H}\ \cos(\theta_L)\dot{\theta}_L + l_{H_{CM}}\ \cos(\theta_H)\dot{\theta}_H)m_H}{l_F(m_L + m_H)} \end{aligned} \tag{5}$$

During the recovery states may go out of this plane by hip flexion/extension.

A MATLAB® program solved the PoR for about 1000 initial states intelligently scattered on the $\hat{x} - \hat{v}$ plane. Average anthropometric parameters (Winter, 2009, see Table 2) were used. Satisfaction of foot constraints is guaranteed and when necessary,