TRUNK STABILITY WHILE STANDING OR SITTING: A STATIC ANALYSIS

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Abstract - *Several neuromuscular disorders cause trunk unstability. External support such as seating aids, orthoses, or external muscle control by FES, are then needed. In this paper, we investigate the static requirement for stabilizing the trunk in the sagittal plane while standing or sitting. A simple biomechanical model is used, composed of two moving segments, the pelvis and the upper trunk. We evaluate the stabilizing effort by the critical stiffness, the minimal linear stiffness required for making the posture stable against the gravity forces. Three basic situations are compared: standing erect, sitting erect unsupported and with a backrest. This preliminary study shows the importance of pelvis posture and motion in stabilizing the trunk. It confirms the importance of pelvis stabilization.*

Keywords: biomechanics, seating, stability, wheelchair

1. Introduction

The torso is the base for arms and head movement. In this paper we focus on trunk stability during standing or sitting. Muscles acting on the spine and pelvis are required to stabilize the trunk, even when no load is carried and the posture fully equilibrated. Several neuromuscular disorders (as Spinal Cord Injury (SCI), Multiple Sclerosis) affect the stability of the trunk.

External aids are then needed for standing (or walking). These aids range from crutches and walkers, standing orthoses and electrical stimulation. When sitting balance is not sufficient, poor postures are corrected in a static way by holding the person in a convenient posture by additional material such as lateral support, shaped cushions and inserts, belts, rigid bars [4]. Even when the achieved posture is correct, long-term static sitting causes loss of joint mobility and increases the risk of pressure sores [5]. Much research and development need to be done in evaluating and improving the current seating aids. Especially, there is a need to stabilize in a functional way, giving the person the ability to change posture. Trunk stabilization is an important issue for FES supported mobility. It is questionable if FES could improve sitting stability.

In this paper, we look at the static requirement for stabilizing the trunk in the sagittal plane while standing or sitting. We first introduce stability analysis on a single degree of freedom (dof) inverted pendulum (§2). This is the simplest model for addressing the problem of postural stability [1]. In part §3, a more realistic two-segment model is presented. Then stability is analyzed in three basic situations: standing erect (§4), sitting erect unsupported (§5) and sitting with a backrest (§6).

2. Stabilization of a 1-dof inverted pendulum

Let us consider a one degree of freedom (dof) joint supporting a segment with mass *m* and center of mass at distance *h* from the joint center of rotation *C* (fig. 1).

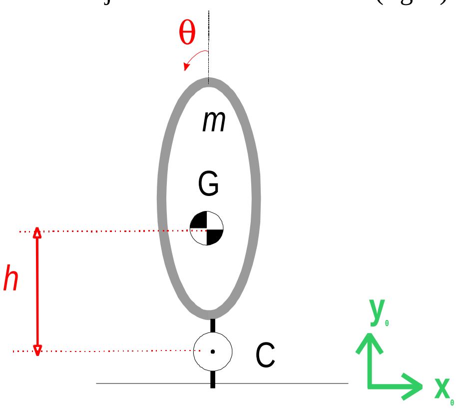


fig. 1 1-dof inverted pendulum

The *gravitational potential energy* is function of the joint angle θ: $V_g = mgh\cos(\theta)$

where θ is zero in the vertically upright position.

When no other forces are added to the system, the upright position is an unstable equilibrium. In order to stabilize the pendulum a feedback of the position disturbance is required. This may be represented by a *linear joint stiffness*: $\tau_s = -k\,(\theta - \theta_k)$

where τ_s is the restoring torque, k is the joint stiffness, and θ_k is the resting position of the spring.

The potential energy of the system is then modified into:

$$V = mgh\cos(\theta) + k/2\,(\theta - \theta_k)^2$$

The equilibrium condition is written:

$$\left.\frac{\partial V}{\partial \theta}\right|_{eq} = 0 \quad \Leftrightarrow \quad \sin(\theta_{eq}) = \alpha_k\,(\theta_{eq} - \theta_k)$$

where $\alpha_k = k/mgh$ is called the *stiffness ratio.*

Static stability is ensured locally at equilibrium when the *total effective stiffness* is positive:

$$K_{eq} = \left.\frac{\partial^2 V}{\partial \theta^2}\right|_{eq} > 0 \quad \Leftrightarrow \quad \alpha_k > \cos(\theta_{eq})$$

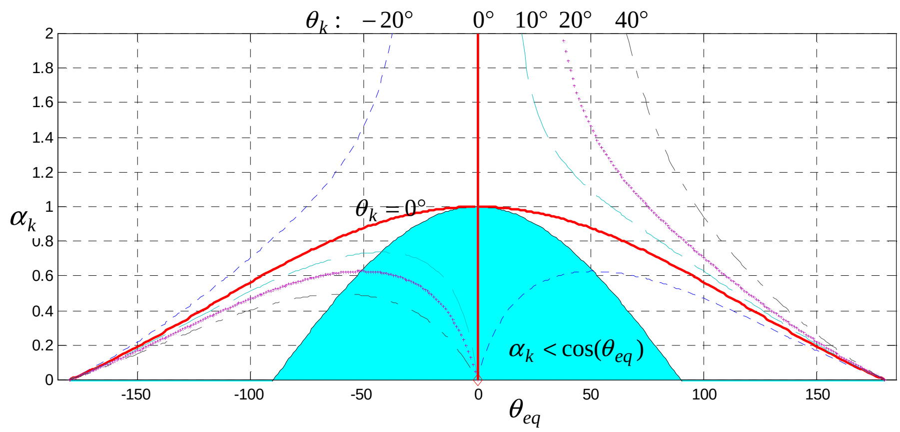
The total effective stiffness K_{eq} is a measure of the stability. Let us consider the system stabilized at position θ_{eq}. The additional torque required moving to another position $\theta = \theta_{eq} + \Delta\theta$ is then:

$$\tau_\theta = \left.\frac{\partial V}{\partial \theta}\right|_\theta \cong \left.\frac{\partial V}{\partial \theta}\right|_{eq} + \left.\frac{\partial^2 V}{\partial \theta^2}\right|_{eq} \Delta\theta = K_{eq}\Delta\theta$$

To provide support without preventing motion, a small effective stiffness should be realized. But to resist again important disturbances, a greater effective stiffness is needed

In fig. 2, the equilibrium positions and the stability limit are drawn. By adjusting the stiffness ratio α_k and the resting position of the spring θ_k, the equilibrium position θ_{eq} and the effective stiffness K_{eq} are controlled independently. This is the principle of impedance control [6], here in his simplest static form.

The linear stiffness required to stabilize is the highest for the upright position $\theta_{eq}=0°$. We call this stiffness $k_{critical}=mgh$, the critical stiffness; it corresponds to stiffness ratio $\alpha_k=1$. If the joint stiffness is higher than the critical stiffness, whatever the resting position of the spring θ_k, there is a single equilibrium position θ_{eq}, which is stable. This means that the total potential energy has a single minimum; global stability is ensured. In the following, we will consider requirements for stabilization in the posture where the gravity forces are equilibrated. This posture will be called the *erect posture*. The erect posture is the more demanding for stiffness, and the less demanding for permanent force. It is the posture best suited to initiate a movement.



For each θ_k, two equilibrium curves (drawn with same style) originate from $\theta=\pm180°$, the original stable equilibrium position of the pendulum. The unstable equilibrium positions are in the gray area, under the curve $\alpha_k=\cos(\theta_{eq})$. The effective stiffness may be obtained as the vertical distance between the equilibrium point considered and the curve $\alpha_k=\cos(\theta_{eq})$.

fig. 2 Equilibrium positions θ_{eq} function of joint stiffness ratio α_k, for different resting position θ_k of the spring

3. The two-segments model

The 2-segments sagittal model (fig. 3) includes two degrees of freedom: the lumbar flexion-extension and the tilt of the pelvis. Lumbar flexion is lumped as a rotation (θ_2) about a centre *C*, located at the L3 vertebra [7][8]. The rotation of the pelvis (θ_1) is about the hip centre *H* when standing; and about a point *I* located on the ischial tuberosities, when sitting. A more accurate model for sitting should consider the rolling of the pelvic bone, but is not required for a local stability analysis. It is assumed that in the erect standing position, the centers of mass are vertically aligned with the joint centers *C* and *H*. The model parameters (table 1) are derived mainly from literature anthropometric data collected in [2] for a 50% percentile male (75.2kg, 1.75m), and also from [7]. 55% of the mass of the lumbar region is assumed to move with the pelvis and 45% with the upper back.

In the following section, we will look at the coupled stability of pelvic tilt (θ_1) and lumbar flexion-extension (θ_2).

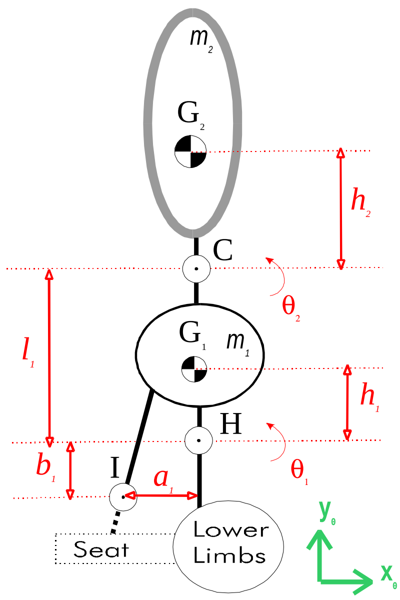


fig. 3 Two-segments model

Pelvis including the lumbar region under L3	mass	m_1=16 kg
	distance from hip center *H* to *C* (L3)	l_1=0.165 m
	distance from *H* to c.o.m	h_1=0.05 m
	position of *I* (ischial tuber.) with respect to *H*	a_1=0.04 m
		b_1=0.06 m
Upper trunk including head, neck and arms.	mass	m_2=35.5 kg
	distance from *C* (*L3*) to c.o.m	h_2=0.10 m

table 1 Model parameters

4. Standing erect

The erect position is ($\theta_{1eq}=0,\theta_{2eq}=0$). Let us consider stabilization of this posture by two linear joint stiffnesses k_1 (hip stiffness) and k_2 (lumbar stiffness) whose resting position are the 0 positions. The condition for stability at equilibrium is that the effective stiffness matrix K_{eq} be definite positive. K_{eq} is function of stiffness k_1 and k_2:

$$K_{eq} = \left.\frac{\partial^2 V}{\partial \theta^2}\right|_{eq} = \begin{bmatrix} k_1 - (\mu_1 + \mu_2) & -\mu_2 \\ -\mu_2 & k_2 - \mu_2 \end{bmatrix}$$

with $\mu_1 = (m_1 h_1 + m_2 l_1) g$, $\mu_2 = m_2 h_2 g$

The stability condition determines a stability area fig. 4. The critical stiffness is now a curve in the plane (k_1,k_2). The asymptotes of the critical stiffness curve correspond to the critical stiffness of the 1-dof pendulum obtained by locking one of the two joints. The point with minimal norm on the critical stiffness curve is circled. The stiffness values corresponding to this point and to the asymptotes are reported in table 1.

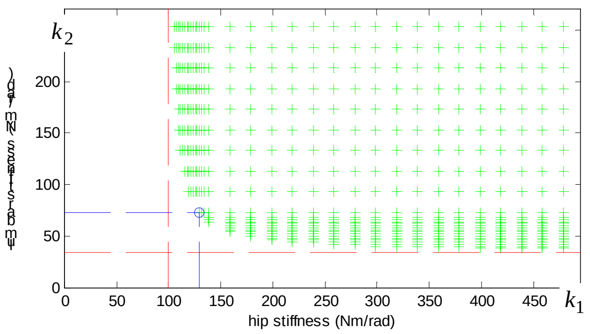


fig. 4 Stable stiffness area for standing erect

5. Sitting erect unsupported

Because the center of mass of the pelvis is not aligned with the center of rotation *I* and *C*; the pelvis must be slightly backward tilted to be in equilibrium:

$$\left.\frac{\partial V_g}{\partial \theta}\right|_{eq} = \underline{0} \Leftrightarrow \begin{cases} \tan(\theta_{peq}) = \dfrac{\mu_{1a}}{\mu_1} \\ \theta_{2eq} = -\theta_{peq} \end{cases} \Leftrightarrow \begin{cases} \theta_{peq} = +12° \\ \theta_{2eq} = -12° \end{cases}$$

where θ_p is the absolute angular position of the pelvis, $\mu_1 = (b_1 m_{12} + m_1 h_1 + m_2 l_1) g$, $\mu_{1a} = a_1 m_{12} g$, $m_{12}=m_1+m_2$.
The lumbar spine is flexed to compensate for the pelvic tilt. The relative angle between the pelvis and the seat depends on the seat pan inclination θ_s: $\theta_{1eq}=\theta_{peq}-\theta_s$.

Let us consider stabilization of this posture by two linear stiffnesses acting on the two degrees of freedom: k_1 (pelvic tilt stiffness) and k_2 (lumbar stiffness). The effective stiffness at equilibrium is:

$$K_{eq} = \begin{bmatrix} k_1 - (\mu_1 \cos(\theta_{peq}) + \mu_{1a} \sin(\theta_{peq}) + \mu_2) & -\mu_2 \\ -\mu_2 & k_2 - \mu_2 \end{bmatrix}$$

Only the contribution of gravity to the effective stiffness on pelvic tilt is modified with respect to the standing erect situation. This causes the vertical asymptote of the critical stiffness curve to be pushed to the right, corresponding to a higher pelvic tilt stiffness value. Note that the results are not influenced by inclination of the seat pan.

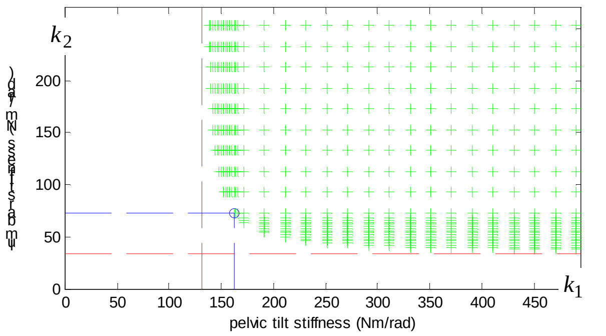


fig. 5 Stable stiffness area for sitting erect

6. Sitting with a backrest

When sitting on a chair with a backrest, the horizontal force applied on the backrest cause the pelvis to slide on the seat forwards while tilting backwards. This results in a posterior-leaning posture [2], which is a typical posture of persons with SCI [5]. To model this situation (fig. 6), we add a degree of freedom to the pelvis motion relative to the seat pan (x_I), and constrain the upper trunk to be parallel to the backrest. We obtain a one-dof motion: pelvic tilt (θ_1), lumbar flexion-extension (θ_2), horizontal displacement of the pelvis (x_I) and vertical displacement of the upper trunk (y_C) being coupled.

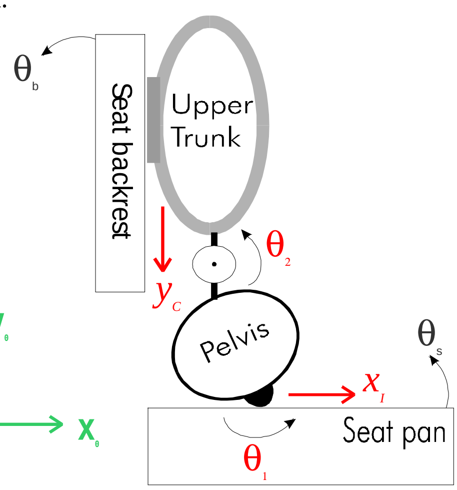
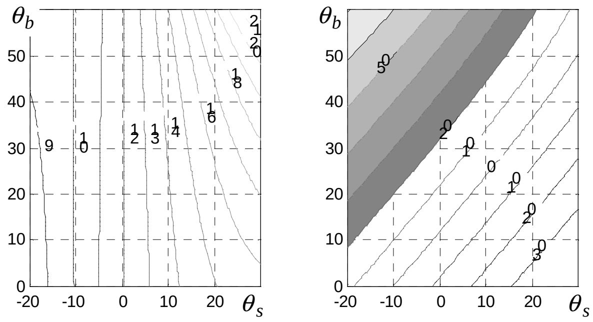


fig. 6 Kinematic model for sitting with a backrest

The condition for equilibrium under gravity forces is: $\tan(\theta_{peq}) = \dfrac{\mu_{1a}\cos(\theta_s) + \mu_{1b}\sin(\theta_s)}{\mu_1\cos(\theta_s) - (\mu_{1a} + \mu_{1c}\tan(\theta_b))\sin(\theta_s)}$

where θ_s and θ_b are the angles of respectively, the seat pan and backrest recline with respect to vertical, $\mu_{1b} = m_{12}(b_1 + l_1)g$ and $\mu_{1c} = m_1(l_1 - h_1)g$.

It is indeed a condition that allows no slip, without shear forces. For moderate recline of the seat pan, the equilibrium position of the pelvis with respect to the seat pan is almost fixed (fig. 7a). Then for important backrest recline, this leads to excessive extension of the lumbar spine (fig. 7b). The seat configurations giving more than 20° lumbar extension for equilibrium are grayed in (fig. 7a,fig. 8).



(a) pelvic tilt/backrest θ_{1eq} (b) lumbar flexion-ext. θ_{2eq}

fig. 7 Equilibrium position sitting with a backrest

The two stiffness k_1 and k_2 now act in parallel. To stabilize this position, the condition is:

$$k_1 + k_2 > k_{critical} = -\left.\frac{\partial^2 V_g}{\partial \theta^2}\right|_{eq}$$

The critical stiffness is not varying much with the seat configuration (fig. 8). It decreases of only 20% for 40° of backrest recline and 20° of seat recline.

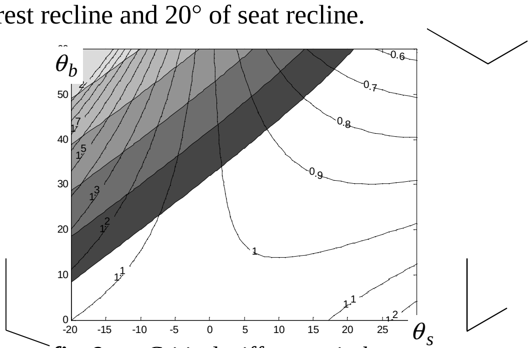


fig. 8 Critical stiffness ratio $k_{critical}/\mu_1$

8. Conclusions

We have considered the stabilization of postures that are equilibrated with respect to respect gravity forces (erect postures). These postures are the more demanding in term of stabilization, but the less in term of forces. The different values of stiffness required to stabilize an erect position are reported in table 1. The stabilization effort is greater for sitting unsupported than standing because of the not optimal alignment of the centers of mass. It is much lower when sitting with a backrest. This is the effect of any rigid support that allows the joints stiffness to act in parallel.

When standing or sitting unsupported, a stiff pelvic stabilization allows to diminish, but not to cancel the lumbar stiffness. Pelvis stabilization is recognized as a main issue in wheelchair seating practice [4], and was shown to improve the functional reach [3]. Stabilization at more relaxed postures is important for long term sitting. Stiffness at the seat interface adapted to the persons must be determined. Changing postures could be achieved using the impedance control concept.

***Critical* *stiffness* (Nm)**		*degrees of freedon*	
		Pelvis rotation	*Lumbar flexion-extension*
Situations	Standing erect	*99*	*∞*
		129	***73***
		∞	*34*
	Sitting erect unsupported	*132*	*∞*
		162	***73***
		∞	*34*
	Sitting erect with backrest	*0*	*98*
		49	***49***
		98	*0*

table 1 Comparison of results

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