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► **To cite this version:**

Sajeeva Abeywardena, Eisa Anwar, Stuart Miller, Ildar Farkhatdinov. Human balance augmentation via a supernumerary robotic tail. the 44th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC'22), Jul 2022, Glasgow, United Kingdom. hal-03644817

**HAL Id: hal-03644817**

**<https://hal.science/hal-03644817v1>**

Submitted on 19 Apr 2022

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# Human balance augmentation via a supernumerary robotic tail

Sajeeva Abeywardena<sup>1</sup>, Eisa Anwar<sup>1</sup>, Stuart Miller<sup>2</sup>, and Ildar Farkhatdinov<sup>1,3</sup>

**Abstract**—Humans are intrinsically unstable in quiet stance from a rigid body system viewpoint; however, they maintain balance thanks to muscular and neuro-sensory properties whilst still exhibiting postural sway characteristics. This work introduces a one-degree-of-freedom supernumerary tail for balance augmentation in the sagittal plane to negate anterior-posterior postural sway. Simulations showed that the tail could successfully balance a human with impaired ankle stiffness and neural control. Insights into tail design and control were made; namely, to minimise muscular load the tail must have a significant component in the direction of the muscle load, mounting location of the tail is significant in maximising inertial properties for balance augmentation and that adaptive control will exploit augmentation characteristic of the tail best for different loads held by a wearer.

## I. INTRODUCTION

Quiet standing analysis has shown that it is valid to model a human in an upright pose as an inherently unstable inverted pendulum[1]–[4]. Due to the musculoskeletal and sensorimotor systems, the toppling torque induced by the gravitational force is negated and humans maintain upright balance so long as their centre of mass (CoM) is within the base of support (BoS). Nevertheless, due to the instability of the natural dynamical system, humans exhibit postural sway whilst in a quiet stance. Coupled with factors such as muscle fatigue, neurological disorders, and loss of vestibular function; the CoM can momentarily shift outside the BoS which is enough to cause the dynamics to become unstable and the human losing balance as a result.

Research has been conducted to augment human balance with robotic assistance. Exoskeletons are directly attached to a wearers natural limbs (NLs), and are used to augment their force capabilities at a joint level. A recent study showed that back support exoskeletons reduced postural sway in quiet stance [5]; whilst other strategies have included applying an assistive torque at the pelvis to provide balance support during gait and the implementation of a stepping strategy for balance recovery [6], [7]. Due to being attached in parallel with the NLs of the wearer; exoskeletons share the same kinematic properties as the assisted limb but the added mass and footprint of the wearable device can hinder the natural motion capabilities of the limbs.

Gyroscopic systems and robotic tails mounted posterior to the trunk have been used to provide human balance assistance with independent kinematic workspaces to the

NLs. In gyroscopic systems, the principal of precession is utilised to counteract the torque caused by postural sway [8], [9]. Whilst these systems provide balance, they come at the cost of significant added mass of 10-16 kg with an extra 10 kg shown to be detrimental to the motion of human NLs [10]. Taking inspiration from animals, robotic tails utilise swinging inertia for balance augmentation [11], [12]. In these systems, the swinging mass ranged between 1.6-2 kg; however, this was achieved via a ground mounted air compressor [11] or a total added system mass of 9 kg [12]. Further, the one-degree-of-freedom (dof) tail in [12] was designed to counteract external perturbations in the coronal plane; therefore, the swinging inertia will not negate anterior-posterior (AP) postural sway induced by gravity.

The previous work in supernumerary tails have shown ability to provide balance for a human; however, a systematic control framework was not utilised. In this work, we propose a one-dof robotic tail for quiet standing balance in the sagittal plane and use state space control for methodical control development. The dynamics of the system is modelled in Section II, a simulation study to examine the effectiveness of the tail to augment balance and impact on muscular load in dorsiflexion conducted in Section III, and the consequences of the presented framework for informed design of robotic assistance discussed in Section IV.

## II. SYSTEM MODELLING AND CONTROL

The traditional model of quiet standing models the human with hands by the side as one rigid body, with one-dof at the ankle joint that acts in the sagittal plane and the CoM of the human located in the axis which gravity acts but in opposing direction. Hence, the torque due to gravitational force in this pose is null and the human will remain balanced unless perturbed by an external disturbance. In many quiet standing scenarios, the arms are conducting a task in front of the torso or holding a load. As such, the CoM of the system (human and load)  $m_s$  is displaced slightly forward, particularly as load  $m_l$  increases. The gravitational torque is no longer null and can lead to instability. Hence, suitable control action is required by the human to maintain the CoM within the BoS. Depending on scenario, increased muscle fatigue and mental tiredness inducing longer neuromechanical delay of the neural control element while negatively impact the ability to maintain upright posture. It is hypothesised that a tail can assist in compensating for the unstable dynamics in the quiet standing model. As these instabilities are induced by a torque created by rotational motion, a simple concept to counteract that is by utilising a one-dof tail that swings in an arc in the sagittal plane as illustrated in Fig. 1.

<sup>1</sup>School of Electronic Engineering and Computer Science, Queen Mary University of London, United Kingdom.

<sup>2</sup>William Harvey Research Institute, Barts & The London School of Medicine & Dentistry, Queen Mary University of London, United Kingdom.

<sup>3</sup>Imperial College of Science, Technology and Medicine, London, UK. mailto: {s.abeywardena, i.farkhatdinov}@qmul.ac.uk

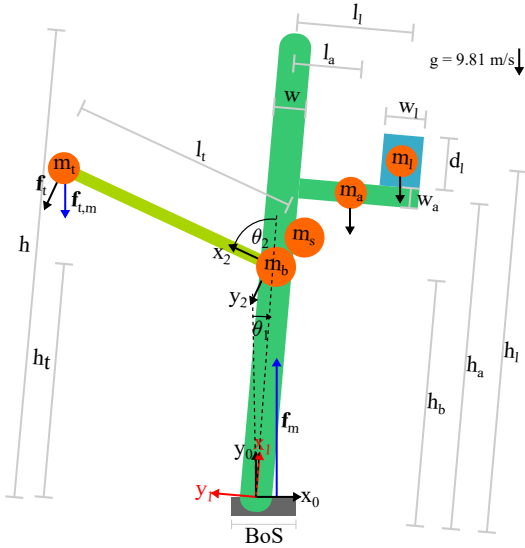


Fig. 1: Conceptual swinging arc tail with frame assignment and geometric parameters

### A. Geometric and Inertial Parameters

Due to the assumption that the human can be modelled as an inverted pendulum in an upright pose, it is suffice to consider the body  $m_b$  (legs, trunk, head), forearm  $m_a$  and load  $m_l$  as one rigid body. Hence, the CoM  $m_s$  of the composite rigid body (CRB) system can be found. This rigid body has one-dof, i.e. the rotation of the ankle about  $\mathcal{F}_0$  by  $\theta_1$ . The conceptual tail is modelled as a separate body mounted to the human at a distance  $h_t$  along the  $x_1$  axis and which swings in an arc through an angle of  $\theta_2$  about  $z_2$ .

### B. Inverse Dynamic Model

The inverse dynamic model (IDM) correlates the generalised forces to the motion states of the joints via an inertial mapping. It can be utilised to calculate the required joint torques to follow a prescribed motion trajectory of an inertial rigid body that could be subjected to external forces. In general, utilising an appropriate method such as Newton-Euler (NE), Euler-Lagrange (EL) or Natural Orthogonal Complement (NOC) [13], [14], the IDM can be written as

$$\mathbf{S}\mathbf{u} + \mathbf{u}_p = \mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{G}(\mathbf{q}) \quad (1)$$

where  $\mathbf{q}$  are the generalised joint coordinates,  $\mathbf{M}$  is the  $n \times n$  generalised inertia matrix,  $\mathbf{C}$  is an  $n \times n$  matrix related to the centripetal and Coriolis torques,  $\mathbf{G}$  the vector of generalised gravity forces,  $\mathbf{u}$  are generalised active forces,  $\mathbf{u}_p$  are generalised passive forces (i.e. joint stiffness) and  $\mathbf{S}$  is an  $n \times n$  diagonal matrix that selects whether the joint is an active (1) or passive (0) input.

### C. Linearised State Model

Equation (1) is of use when the trajectory of the generalised co-ordinates is known a-priori and the associated generalised forces are required. However, in many situations, it is of more use to analyse the behaviour of the dynamical system from the perspective of the motion variables, i.e.

human balance. This is known as the forward dynamic model (FDM), i.e. the dual model to the IDM whereby

$$\ddot{\mathbf{q}} = -\mathbf{M}^{-1}(\mathbf{C}\dot{\mathbf{q}} + \mathbf{G}) + \mathbf{M}^{-1}(\mathbf{S}\mathbf{u} + \mathbf{u}_p) \quad (2)$$

From Eq. (2), it is evident that the generalised inertia matrix is critical in the open loop response of the system, and how a control input is transformed to impact the system response. This is a set of non-linear second-order ordinary differential equations (ODEs) which can be transformed into a system of first order ODEs by defining the state vector  $\mathbf{x} = [\mathbf{q}^T, \dot{\mathbf{q}}^T]^T$ . Due to the non-linearity that encompasses the workspace of the system, control input design can be complex. However, if only a sub-workspace is of operational interest, the dynamics can be linearised about a stationary point  $(\bar{\mathbf{x}}, \bar{\mathbf{u}})$ ; allowing for concepts of linear time invariant systems to be applied. This is the case for human balance where the operational point of interest is the upright posture. As such, the linearised dynamics about the stationary point can be expressed as the system of first order linear ODEs,

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \quad (3)$$

where  $\mathbf{A}$  and  $\mathbf{B}$  are the linearised state and input matrices.

For the swinging arc tail proposed, the state vector is defined as  $\mathbf{x} = [\theta_1, \theta_2, \dot{\theta}_1, \dot{\theta}_2]^T$  and is linearised about the upright stance posture  $\bar{x}_1 = \bar{\theta}_1 = 0$ . The stationary value of the tail,  $\bar{x}_2 = \bar{\theta}_2$  is the angle which statically balances the system in upright pose. With reference to Fig. 1, summing torques due to gravity around the ankle joint yields

$$\bar{\theta}_2 = \arcsin\left(\frac{m_a l_a + m_l l_t}{m_t l_t}\right) \quad (4)$$

Thus, the stationary point about which the system is linearised is dependent on the mass of the load being held. Further, from Eq. (4), a constraint exist on the properties of tail length and mass (hence, inertial capabilities) such that the system can be statically balanced, i.e.  $m_t l_t \geq m_a l_a + m_l l_t$ .

### D. Control Inputs

With the model of the system defined, an understanding of the control inputs is required. The selection matrix which dictates if the modelled joint is active or passive is  $\mathbf{S} = \text{diag}([0, 1])$  as the first row of Eq. (1) correspond to the torque of the ankle and the second to the tail torque. It was initially proposed that humans maintain upright posture due solely to a stiffness control model employed by the ankle [1]; however, it was shown that the stiffness required exceeded physiological values and hence a neural control element assists in providing balance [2], [3]. These properties can be modelled as passive inputs  $\mathbf{u}_p$  in terms of the states of the ankle [3], [4], i.e.

$$\begin{aligned} \mathbf{u}_p &= \mathbf{u}_{ank} + \mathbf{u}_{nm} & \mathbf{u}_{ank} &= \kappa_p (\bar{\theta}_1 - \theta_1) + \kappa_d (\dot{\bar{\theta}}_1 - \dot{\theta}_1) \\ \mathbf{u}_{nm} &= k_p (\bar{\theta}_1 - \theta_1 (t - \tau_d)) + k_d (\dot{\bar{\theta}}_1 - \dot{\theta}_1 (t - \tau_d)) \end{aligned} \quad (5)$$

where  $\mathbf{u}_{ank}$  is an impedance model of the ankle joint and  $\mathbf{u}_{nm}$  is the neural control input represented by a proportional-

derivative control with time delay  $\tau_d$ .

The time delay changes the state equation governed by Eq. (3) from a system of first order ODEs into a delay differential equation (DDE). As a consequence, the characteristic equation of the system is now a quasi-polynomial which has infinite poles (eigenvalues), complicating control design. However, as  $\tau_d \rightarrow \infty$ , the delay becomes insignificant in terms of control. For human balance, this is symbolic of increasing strain on the neuro-controller due to mental tiredness, inherent motor control disorders or loss of vestibular function, i.e. situations where the tail is of increased value to circumvent loss of balance. Including the passive control element  $\mathbf{u}_{ank}$ , assumes that the ankle will be able to provide a consistent level of compensatory torque and does not factor in muscle fatigue. As such, any ability of the tail to reduce muscular fatigue is void by including this term. Hence, to investigate the potential of a tail to augment human balance whilst reducing muscular load, the worst case scenario of large neuromechanical delay and no resistive ankle torque is considered, i.e.  $\mathbf{u}_p = 0$ . As such, there is only one input to the system, the torque of the tail represented by  $\mathbf{u}$ .

### E. Force Analysis

A hypothesis of the tail is that muscular load in quiet standing for able-bodied users will be reduced. A force analysis can be conducted to investigate this assertion. The compensatory torque to AP sway of the ankle is created by the plantar and dorsiflexors. When the CoM exceeds the BoS, the ankle must dorsi-flex to oppose gravity. To investigate the impact the tail has on muscle force, the overall tail force can be projected into a component that acts in the direction of the dorsiflexors when  $\dot{\theta}_1 < 0$ . A line model of the dorsiflexor is used, where it attaches half way from the forefoot up to the top of tibia (0.5 m [15]) as illustrated in Fig. 1. For this analysis,  $\kappa_p = 494$  Nm/rad and  $\kappa_d = 30$  Nm-s/rad [4].

## III. SIMULATION

A simulation of the human-tail system in Fig. 1 was conducted, with and without a 5 kg load held.

### A. Parameters

The geometric and mass parameters<sup>1</sup> related to Fig. 1 are tabulated in Table I where the anthropometric parameters are derived from [15]. The length of the tail was fixed at 0.9 m, in line with [12] and a swinging mass of 5 kg selected. Note, in [12], the human was 22 kg less than here and the ability to maintain balance was assumed in control. The tail was simulated at two heights, the CoM of the body i.e.  $h_b$  and 20 cm above at 1.2 m (around mid back) to ensure ground clearance and investigate the effect of added inertia. The inertia of the human in the sagittal plane was 12.9 kg-m<sup>2</sup> [15]. The BoS was defined as a foot of 0.25 m with a rearfoot to forefoot ratio of 0.08:0.17 [16]. As such, the CoM exceeds the BoS when  $\theta_1 = 9.5^\circ$ . Full state feedback control laws of  $\mathbf{u} = -\mathbf{K}\mathbf{x}$  were developed, with the effect of non-dominant

<sup>1</sup>Note, for the arm,  $l_a$  is reported as half the total length of the segments and the mass corresponds to two arms.

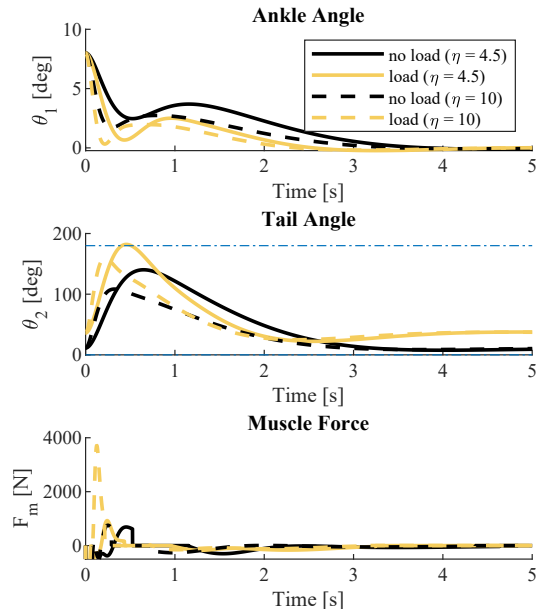


Fig. 2: Simulation with the tail mounted at the CoM

pole placement ( $\eta = 4.5, 10$ ) which dictates magnitude of control gains (i.e. tail torque) investigated. Settling time was set at 4 seconds and damping  $\zeta$  tuned to ensure the tail did not hit the body at the height of 1.2 m for load and no load.

TABLE I: The geometric and mass parameters for the Human-Tail model with respect to Fig. 1. Distances have units of metres and mass in kilograms.

Segment ( $i$ )	$h_i$	$l_i$	$w_i$	$d_i$	$m_i$
Body ( $b$ )	0.997		0.15	1.8 ( $h$ )	78.2
Arm ( $a$ )	1.11	0.225	0.0958		4
Load ( $l$ )	1.23	0.354	0.193	0.15	0/5

### B. Results and Discussion

The human-tail system was simulated with an initial condition of  $\mathbf{x}_0 = [8^\circ, 0, 0, 0]$ , i.e. when the CoM is about to exceed the BoS. In a physical realisation, the controller would aim to prevent the human from reaching this posture. Figures 2 and 3 show the results of the simulation at the two mounting height levels. From the simulation it is evident that the proposed tail can provide balance with and without load. The tail being higher allowed for more clearance from the body due to the extra inertia, with lower  $\theta_2$  values. Further, the trajectory of the tail is lower magnitude and settles quicker with  $\eta = 10$ , i.e. when the non-dominant poles are further away. The caveat to this is that greater torque is required which can impact the amount of force required from the antagonistic muscle in the case of an able human. Further, more damping was used to balance the system with no load (0.75) compared to load (0.6), indicating that an adaptive control methodology would be required for a fully encompassing system that considers multiple load cases.

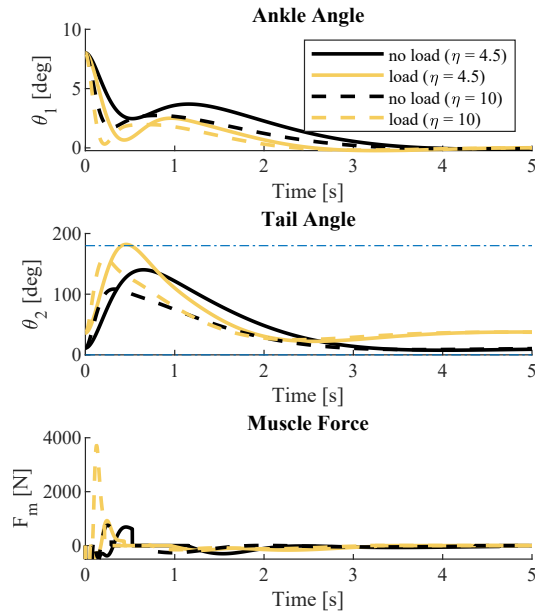


Fig. 3: Simulation with the tail mounted at mid back level

It was hypothesised that muscle force could be reduced with the tail. However, due to its rotational nature, reduction in muscle force will only be apparent when the tail force has a significant component in the direction of the muscle. This result is critical, as it is useful for informed design of a tail; suggesting that a one-dof revolving tail is not the most optimal solution if reducing muscle force is the key criteria. Nevertheless, this simulation considered the worst case scenario of no ankle stiffness control and severely impaired neural control. As such, these results proved the validity and provide an upper bound on the requirements for a one-dof revolute tail to negate AP sway in the sagittal plane, i.e. for a tiring warehouse worker holding load, the tail will be beneficial to maintain upright posture as fatigue sets in and AP sway becomes apparent. For a physical realisation of the tail, the required motion and torque will be reduced due to the musculoskeletal and sensorimotor system providing extra resistive torque. Hence, the mass and length of the tail that dictate the inertial properties to create the compensating torque can be reduced based on the level of assistance required for the potential tail application, i.e. reduction in muscle loads for physically able versus full balance augmentation of those with motor impairment.

#### IV. FUTURE WORK

It was shown that a simple one-dof revolute tail is able to provide human balance augmentation of AP sway in the sagittal plane. A key outcome of this work is the systematic approach to the control which can lead to informed design of robotic tails. This study and previous work of other authors show the importance in maximising the inertia of the tail to provide a counteracting torque. However, increasing mass and length have consequences, i.e. added strain on the body and workspace implications. Potential future avenues with this in consideration are to select an application of the tail to

determine the level assistance required; include the delay dynamics of neural control which provide added stabilisation to the system and hence reduce the level of assistance required from the tail; and to investigate tails with added dofs which could add inertia to the system with a wider workspace and allowing for two control goals, i.e stabilisation and muscle load. Hence, this work has shown critical considerations for the field of physical human-robot interaction where logical simulation can lead to design which successfully achieve the desired task while minimising impact on a human.

#### ACKNOWLEDGEMENT

This research was conducted with funding from UKRI EPSRC project EP/T027746/1. We thank Etienne Burdet for valuable discussions.

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