Augmenting Human Balance with Wearable Robotics for Load Handling Tasks

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***Abstract*— In this preliminary work, we propose a concept of a wearable robotic tail to augment human balance in load carrying and manipulation tasks assisted by supernumerary robotic limbs. The robotic tail is controlled to counter balance the load for maintaining stable posture based on the centre of mass feedback information. Validation tests with a computer model demonstrate the feasibility of the proposed concept and provide useful input on the system design and the mechanical power required for the robotic tail.**

I. Introduction

Workers in industries such as construction and logistics are regularly required to carry heavy loads. If this is done with poor posture then it can cause back problems into older age [1]. Carrying heavy loads puts considerable strain on posture muscles and increases compression forces on the spine. Over 40% of workers in manual building trades have had back problems [2]. Wearable robots such as exoskeletons and supernumerary (extra) limbs can provide physical assistance to increase the capability and productivity of workers or help them to maintain these attributes into older age [3]–[6]. While exoskeletons are shown to be effective at reducing the load for their users, very few of the robots support the balancing function [7]–[9]. Other approaches to assist posture control during load carrying include using wearable gyroscopic mechanisms [10] or employing robotic superlimbs to increase the base of support [11].

We consider a system composed of a healthy human-worker assisted by supernumerary robotic limbs, as shown in Fig. 1a. Even if the material handling task is assisted by the robotic limbs, human posture control and balancing might become more challenging as the centre of mass (CoM) of the total system is shifted anteriorly beyond the base of support (BoS) determined by the user's feet position. To assist balancing we propose a concept of a wearable robotic tail that automatically adjusts its orientation to counter balance the workload (as shown in Fig. 1).

In this work we would like to explore if a wearable robotic tail can augment balance capabilities of a user assisted by supernumerary limbs for load carrying tasks. To the best of the authors knowledge, usage of wearable robotic mechanisms such as the proposed tail was not proposed previously. Nabeshima et al [12] have described a design concept of a wearable bioinspired robotic tail (which could be potentially used to support balance) but no results on the balancing functionality were presented. In the next sections we present the mechanical model of a human performing material carrying task with and without balancing assistance provided by the wearable robotic tail. Through a simulation study we demonstrate that the robotic tail helps to augment human balancing with a simple feedback control and we obtain important information on required mechanical power important for future system design and actuation.

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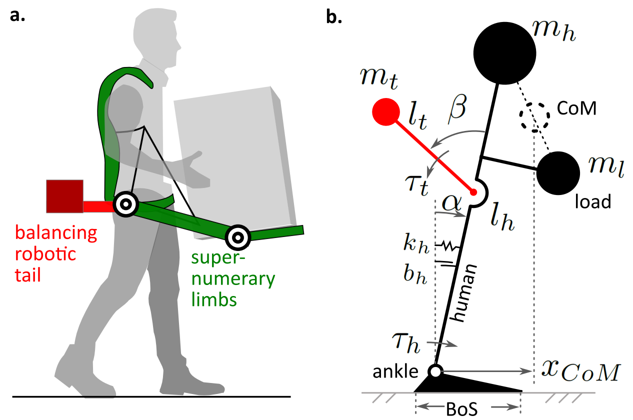

Fig. 1: **a:** a user carrying a load assisted by the supernumerary limbs and the balancing robotic tail. **b:** the mechanical model used for simulation.

II. Modelling Balancing with Robotic Tail

We consider a standing healthy user assisted with supernumerary robotic limbs to carry a heavy object (Fig. 1a). The mechanical model used in the simulations is shown in Fig. 1b. The model includes an inverted pendulum (l_h=1.75 m, m_h=75 kg) with ankle joint actuation to model the user [13]. The stiffness of the ankle joint (k_h=10 Nm/deg) and its damping (b_h=10 Nm·s/deg[1]) were selected based on [14]. The physical object carried by the human was modeled as a point mass (m_l=10 kg) rigidly attached to the pendulum. A robotic tail was modelled as a second actuated pendulum attached to the first one below its CoM. The length of the robotic tail was set to l_t=0.9 m and its mass to m_t=4 kg. The model defined the human body sway and robot tail operation in the sagittal plane and the masses were subject to the gravitational acceleration $g = 9.81$ m/s^2.

[1]larger value of b_h was used to improve stability of the inverted pendulum

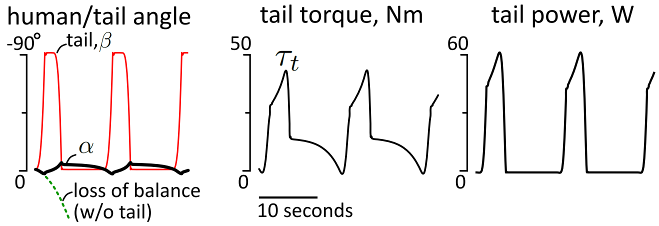

Fig. 2: Simulation results. Time histories of human's and robotic tail's angular orientation (left), torque produced by the tail's controller (middle), and power produced by the tail (right). The dashed green line on the left plot corresponds to the simulation test without the robotic tail (unstable case, rapid loss of balance is observed). All plots have the same time scale (total simulation time was 30 seconds).

The model was implemented in Matlab SimMechanics (Mathworks, USA). The model's state included the angular orientation and velocities of the inverted pendulum (human) and the robotic tail $z = (\alpha\ \dot{\alpha}\ \beta\ \dot{\beta})^\top$ (see Fig. 1b). The initial conditions were set to $z = (0\ 0\ 0\ 0)^\top$ In this preliminary study a simple linear feedback control approach with gravity compensation for the robotic tail was used:

$$\tau_t = k_p\alpha + k_d\dot{\alpha} + m_t l_t g \sin(\beta - \alpha) \tag{1}$$

with constant controller gains $k_p = 200$ Nm/rad and $k_d = 20$ Nm·s/rad. The aim of the controller was to maintain the human body upright so that the resulting CoM of the system remained within the BoS. In addition to the linear PD-controller, the control for the robotic tail included gravity compensation to reduce the static component (weight) in order to reduce the torque levels for the tail's actuator. This gravity compensation system could be achieved in practice by using passive gravity compensation mechanisms (for example, mounting a spring on the tail which adds an upward force to the tail based on its extension).

III. Results and Discussion

Fig. 2 shows the simulation results for two cases: 1) balancing with no robotic tail (only human with extra load, green dashed line on the left plot); and 2) balancing with the robotic tail controlled using (1). In the first case a loss of balance is observed as the human's body quickly loses orientation and becomes unstable (human body tilts forward by more than 20° within first five seconds). In the second scenario the human posture is balanced and the system is actively stabilised by the action of the robotic tail (red line in Fig. 2). Simulation showed that when the total CoM moved forward a torque, τ_t, was produced to rotate the tail counterclockwise, lowering it and providing the stabilising input. The opposite was done when the human was leaning backwards as a result of the tail over-correcting. Fig. 2 also shows the torque and power generated by the robotic tail. It shows the peak torque of approx. 45 Nm and maximum power of 60 W which is useful for designing the actuation mechanism for a future prototype of the system. Technically, it is feasible to drive the tail from a relatively small and light electric motor with such power capabilities.

As observed the motion of the tail is characterised by large magnitudes which might not be desirable in practical applications. Furthermore, the system requires continuous stabilisation action, and therefore it can be characterised as non-asymptotically stable. Therefore, a thorough design and analysis for the robotic tail control is required in the future. Ankle joint state was used for the feedback control. In real application, that information can be replaced by the CoM displacement and velocity measured with the help of wearable inertial sensors. Finally, gravity compensation was used in the tail controller, meaning that only dynamic effects for counter-balancing action were stabilising the overall system. The role and requirement for gravity compensation in the controller design will be explored in the future.

References

[1] M. R. Ahasan, S. Väyrynen, and H. Kirvesoja, "Physical workload analysis among small industry activities using postural data," *International Journal of Occupational Safety and Ergonomics*, vol. 2, no. 1, pp. 27–34, 1996.

[2] P. Vendramin and G. Valenduc, "Occupations and ageing at work - an analysis of the findings of the fifth european working conditions survey (october 30, 2012). etui working paper."

[3] A. Chu, H. Kazerooni, and A. Zoss, "On the biomimetic design of the berkeley lower extremity exoskeleton (bleex)," 2005.

[4] N. Settembre, P. Maurice, J. Paysant, J. Theurel, L. Claudon, H. Hani, B. Chenuel, and S. Ivaldi, "The use of exoskeletons to help with prone positioning in the intensive care unit during covid-19," *Annals of physical and rehabilitation medicine*, 2020.

[5] C. Davenport, F. Parietti, and H. H. Asada, "Design and biomechanical analysis of supernumerary robotic limbs," in *Dynamic Systems and Control Conference*, vol. 45295. American Society of Mechanical Engineers, 2012, pp. 787–793.

[6] L. Treers, R. Lo, M. Cheung, A. Guy, J. Guggenheim, F. Parietti, and H. Asada, "Design and control of lightweight supernumerary robotic limbs for sitting/standing assistance," in *2016 International Symposium on Experimental Robotics*, D. Kulić, Y. Nakamura, O. Khatib, and G. Venture, Eds. Cham: Springer, 2017, pp. 299–308.

[7] S. Hyon, J. Morimoto, T. Matsubara, T. Noda, and M. Kawato, "Xor: Hybrid drive exoskeleton robot that can balance," in *2011 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2011, pp. 3975–3981.

[8] I. Farkhatdinov, J. Ebert, G. van Oort, E. van Asseldonk, and E. Burdet, "Human balance augmentation with lower limb exoskeleton robot," 2017.

[9] I. Farkhatdinov, J. Ebert, G. Van Oort, M. Vlutters, E. Van Asseldonk, and E. Burdet, "Assisting human balance in standing with a robotic exoskeleton," *IEEE Robotics and automation letters*, vol. 4(2), 2019.

[10] D. Lemus, A. Berry, S. Jabeen, C. Jayaraman, K. Hohl, F. C. T. van der Helm, and A. J. . H. Vallery, "Controller synthesis and clinical exploration of wearable gyroscopic actuators to support human balance," 2020.

[11] F. Parietti, K. C. Chan, B. Hunter, and H. H. Asada, "Design and control of supernumerary robotic limbs for balance augmentation," in *2015 IEEE International Conference on Robotics and Automation (ICRA)*, 2015, pp. 5010–5017.

[12] J. Nabeshima, M. Y. Saraiji, and K. Minamizawa, "Prosthetic tail: Artificial anthropomorphic tail for extending innate body functions," 2019.

[13] D. A. Winter, F. Prince, and A. Patla, "Validity of the inverted pendulum model of balance in quiet standing," *Gait & Posture*, vol. 2, no. 5, pp. 153–154, 1997.

[14] S. T. E., G. Jaspret, L. M. D., and R. R. F., "Intrinsic ankle stiffness during standing increases with ankle torque and passive stretch of the achilles tendon," *PLOS ONE*, vol. 13, no. 3, pp. 1–21, 03 2018.