Robotic Assistance for Human Balance

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I. INTRODUCTION

Reducing falls is an urgent challenge in aging societies, as falls are among the most frequent causes of hospitalization and death among the elderly [1]. A key factor leading to falls is degraded balance control capability [2]. A robotic assistive device could reduce the risk of falls, with two major prerequisites: A control strategy that cooperatively interacts with human balance control, and a suitable hardware solution to embed this functionality.

Humans use multiple strategies to maintain balance during standing and locomotion. The "ankle strategy" moves the Zero Moment Point (ZMP) [3]. The "hip strategy" moves the upper body in the opposite direction with respect to the lower body, changing the body's angular momentum. Ankle and hip strategy are dominant during stance [4]. Balance control during locomotion is predominantly effected by foot placement [5], [6]. The arms also play a role in maintaining balance during gait [7] by changing angular momentum. To detect situations where balance assistance is needed, important work has been done on modeling [5], [8] and sensor instrumentation [9]. Also controllers for robotic exoskeletons have been suggested that can theoretically upright a passive human subject at the verge of falling [10]. However, the question remains how a human and a robotic assistive device interact in balance control and balance recovery.

Multiple robotic hardware solutions have been suggested for balance assistance; Training devices like the KineAssist [11], the LOPES [12], or training devices for standing [13], are mostly connected to an inertial frame. This set-up allows the device to generate nearly arbitrary assistive forces. However, such devices are not practical for everyday use because of their limited range. Portable solutions include powered exoskeletons, which can influence the movement of individual joints. In doing so, the devices can reinforce ankle or hip strategy, or assist in proper foot placement [10], [14]. However, most available exoskeletons like the eLEGS (Ekso Bionics, US), or the ReWalk (Argo Medical Technologies, Israel) are designed to be strong enough to move paraplegic legs, which makes them bulky, heavy, and complicated to use. Furthermore, these exoskeletons are not primarily designed to assist balance, and even require crutches to use. Finally, for use in daily life, usability and cosmetics play a crucial role. In order to make an assistive robotic device acceptable for a large number of patients, it has to be unobtrusive, effective, convenient, and inexpensive.

First, we address the question of collaborative human-robot balance control on a stationary training device. Then, we investigate how balance assistance can be transferred to a patient's daily life by a portable solution.

II. COLLABORATIVE BALANCE CONTROL

Two major points need to be considered during control design for balance assistance: First, a robotic support system should not override human control, because the human would adapt to the support and increasingly rely on it [15]. To avoid such maladaptation, a device should only assist as needed [16], [15], providing just the support necessary to fulfill a task, in this case balance recovery. Second, whenever two controllers simultaneously generate input signals within a closed loop, missing coordination between them can compromise stability.

To address these challenges, we suggest a strategy where the robotic device only generates *open-loop assistance*, which is *triggered at the instant when loss of balance is detected*. The feed-forward trajectory is calculated based on a model of the falling human, and it is designed such that it uprights the person given that model assumptions are true. Such a control law can be implemented in a computationally efficient way by modeling the human as a linear inverted pendulum, and by paramterizing the force profile as a trapezoidal trajectory of variable duration [17]. Then, the differential equations can be solved algebraically, yielding the duration in function of a given initial state of the human, characterized by the extrapolated center of mass [5].

We conducted a first experimental study on the Lokomat gait rehabilitation robot [18], to evaluate how humans interact with and perceive the assistance. Three unimpaired subjects performed challenging tasks (stand on one leg, walk along a line) while being assisted by the robot when they lost balance. Results show that feed-forward uprighting control restores balance during standing and gait, but the assistance was not perceived very comfortable.

III. WEARABLE BALANCE ASSISTANCE

To transfer balance assistance to a patient's daily life, we investigate a robotic solution that combines portability and

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simplicity. The device is based on a gyroscope assembly that is mounted onto the upper body via a backpack [19]. A gyroscope can generate torques in two different ways: When a spinning reaction wheel is rotated about a gimbal such that the orientation of the spin axis changes, a torque about a third, perpendicular axis is produced; this is the effect exploited by conventional control moment gyroscopes (CMGs). Angular acceleration of the reaction wheel about its axis can also be used to allow the generation of opposing inertial moments on a connected body. A variable-speed control moment gyroscope (VSCMG) combines both effects [20], [21], avoiding singularities. In order to reduce torque and power requirements, it is beneficial to exploit the CMG control mode as much as possible. The general feasibility of gyroscope-based balance assistance has already been investigated for bipedal robots [22], but only the CMG effect of a single gyroscope was used in that simulation study, limiting the range of its effectiveness. To react flexibly to falls in any direction while avoiding singularities, we use an assembly of three VSCMGs. We derive the control law based on a constrained optimization: The constraints ensure that the desired torque is tracked by the assembly, and the cost function guides the use of the CMG and of the reaction wheel mode of each VSCMG, minimizing actuator effort.

For a first proof-of-concept, we simulated a worst-case scenario: A person does not apply any balance-recovering actions, but instead falls rigidly, with hip and knee joints stiff, and no ankle torques applied. Simulation results show that it is possible to return the person to a vertical position from an engagement angle of 10 degrees from vertical, with peak power requirements in the range of 100 W, and peak actuator torques in the range of 15 Nm [19]. This indicates that a portable solution integrated within a backpack would be technologically feasible.

IV. OPEN QUESTIONS

A key question is how wearable devices for locomotion assistance should interface with the human in terms of control. For example, should a wearable assistive device override all human control once the human is on the verge of falling? Such a strategy might be risky, because two controllers in conjunction can lead to instability, in particular if the robot controller is too weak to counteract arbitrary human actions. Open-loop assistance, as suggested in this contribution, avoids these stability issues. However, successful uprighting depends on the actions of the human, and this questions remains to be investigated with more subjects and with patients. Concerning hardware, minimization and tailoring devices to very specific deficits/tasks (like balance control) could make wearable locomotion assistance more practical and convenient for elderly users. However, the strategy sacrifices versatility, and the devices may be useful only for a very small population.

REFERENCES

[1] V. Scott, M. Pearce, and C. Pengelly, “Deaths due to falls among Canadians age 65 and over,” Public Health Agency of Canada, Tech. Rep., 2005.

[2] G. F. Fuller, “Falls in the elderly,” *American Family Physician*, vol. 61, no. 7, pp. 2159–68, 2173–4, 2000.

[3] P. Sardain and G. Bessonnet, “Forces acting on a biped robot. Center of pressure-zero moment point,” *IEEE Transactions on Systems, Man and Cybernetics, Part A*, vol. 34, no. 5, pp. 630–637, 2004.

[4] A. D. Kuo and F. E. Zajac, “Human standing posture: multi-joint movement strategies based on biomechanical constraints,” *Progress in Brain Research*, vol. 97, pp. 349–58, 1993.

[5] A. L. Hof, “The ’extrapolated center of mass’ concept suggests a simple control of balance in walking,” *Human Movement Science*, vol. 27, pp. 112–125, 2008.

[6] M. A. Townsend, “Biped gait stabilization via foot placement.” *Journal of Biomechanics*, vol. 18, no. 1, pp. 21–38, 1985.

[7] S. M. Bruijn, O. G. Meijer, P. J. Beek, and J. H. van Dieën, “The effects of arm swing on human gait stability.” *J Exp Biol*, vol. 213, no. Pt 23, pp. 3945–3952, Dec 2010.

[8] A. Goswami and V. Kallem, “Rate of change of angular momentum and balance maintenance of biped robots,” in *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA)*, vol. 4, apr. 2004, pp. 3785 – 3790 Vol.4.

[9] M. Kangas, A. Konttila, P. Lindgren, I. Winblad, and T. Jämsä, “Comparison of low-complexity fall detection algorithms for body attached accelerometers.” *Gait Posture*, vol. 28, no. 2, pp. 285–291, Aug 2008.

[10] Y. Takahashi, H. Takahashi, K. Sakamoto, and S. Ogawa, “Human balance measurement and human posture assist robot design,” in *Proceedings of the SICE Annual Conference*, 1999, pp. 983 –988.

[11] J. Patton, D. A. Brown, M. Peshkin, J. J. Santos-Munné, A. Makhlin, E. Lewis, E. J. Colgate, and D. Schwandt, “KineAssist: design and development of a robotic overground gait and balance therapy device.” *Top Stroke Rehabil*, vol. 15, no. 2, pp. 131–139, 2008.

[12] J. F. Veneman, R. Ekkelenkamp, R. Kruidhof, F. van der Helm, and H. van der Kooij, “A Series Elastic- and Bowden-Cable-Based Actuation System for Use as Torque Actuator in Exoskeleton-Type Robots,” *International Journal of Robotic Research*, vol. 25, no. 3, pp. 261–281, 2006.

[13] Z. Matjacic, S. Hesse, and T. Sinkjaer, “BalanceReTrainer: a new standing-balance training apparatus and methods applied to a chronic hemiparetic subject with a neglect syndrome,” *NeuroRehabilitation*, vol. 18, pp. 251–9, 2003.

[14] H. K. Kwa, J. Noorden, M. Missel, T. Craig, J. Pratt, and P. Neuhaus, “Development of the IHMC Mobility Assist Exoskeleton,” in *IEEE International Conference on Robotics and Automation (ICRA)*, may. 2009, pp. 2556 –2562.

[15] J. L. Emken, J. E. Bobrow, and D. J. Reinkensmeyer, “Robotic movement training as an optimization problem: designing a controller that assists only as needed,” in *Proceedings of the IEEE International Conference on Rehabilitation Robotics (ICORR)*, 2005, p. 307.

[16] L. L. Cai, A. J. Fong, C. K. Otoshi, Y. Liang, J. W. Burdick, R. R. Roy, and V. R. Edgerton, “Implications of assist-as-needed robotic step training after a complete spinal cord injury on intrinsic strategies of motor learning,” *Journal of Neuroscience*, vol. 26, no. 41, pp. 10 564–8, 2006.

[17] H. Vallery, C. O’Brien, A. Bögel, and R. Riener, “Cooperative Control Design for Robot-Assisted Balance during Gait,” *at-Automatisierungstechnik*, vol. accepted for publication, 2012.

[18] R. Riener, L. Lünenburger, I. Maier, G. Colombo, and V. Dietz, “Locomotor training in subjects with sensori-motor deficits: an overview of the robotic gait orthosis lokomat,” *Journal of Healthcare Engineering*, vol. 1, no. 2, pp. 197–216, 2010.

[19] D. Li and H. Vallery, “Gyroscopic Assistance for Human Balance,” in *Proceedings of the 12th International Workshop on Advanced Motion Control (AMC)*, Sarajevo, Bosnia and Herzegowina, March 2012.

[20] K. A. Ford and C. D. Hall, “Flexible Spacecraft Reorientations Using Gimbaled Momentum Wheels,” *Advances in the Astronautical Sciences, Astrodynamics*, vol. 97, pp. 1895–1914, 1997.

[21] H. Schaub, S. R. Vadali, and J. L. Junkins, “Feedback Control Law for Variable Speed Control Moment Gyros,” *Journal of the Astronautical Sciences*, vol. 46, no. 3, pp. 307–328, 1998.

[22] T. C. F. Wong and Y. S. Hung, “Stabilization of biped dynamic walking using gyroscopic couple,” in *Proc. IEEE International Joint Symposia on Intelligence and Systems*, Nov. 4–5, 1996, pp. 102–108.