Compliant and Efficient Walking

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***Abstract*— To achieve humanlike locomotion in robotics an equilibrium between active and passive walkers should be found. With the latter kind of walkers already being based on the human principle of locomotion and walking energy-efficiently with compliant legs. Quantitative measures for the human likeness of gait are, however, not yet developed. Two ways for comparing gaits, namely specific cost of transport and Froude number, are discussed.**

I. Introduction

In robotics two kinds of walking robots are distinguished. 'Active walkers' is a group name for walking robots using the control paradigm of precise joint-angle control. Their actuators are controlled continuously to follow imposed trajectories, usually in a closed loop. The control structures and actuators used for active walkers are similar to those in industrial robots. Active walkers are usually driven by traditional servomotors with high-gear transmissions to reduce rotational speed and increase torque. Their goal is to reach and maintain a desired position as quick as possible, regardless of the external forces acting on the actuator, within the limits of the actuator. The aim is to approach infinite impedance and make the driven joint as stiff as possible, hence the term stiff actuators. Such drives are excellent for precise position control, as is the principle of the control of active walkers. Consequently active walkers are able to complete various complex tasks and can show high robustness to perturbations. A drawback is that they have high energy consumptions and are energy-inefficient.

On the other hand we have passive walkers which originate from the idea of passive dynamic walking introduced by McGeer [1], who was inspired by the findings that the motion of the swing leg during human locomotion is merely the result of gravity working on an unactuated double pendulum [2]. The motion of a pendulum under influence of gravity when released or propelled from a position different than its equilibrium position is the natural motion of this mechanism. The natural frequency of this motion can be tuned by changing the inertias and lengths of the limbs. Electromyography measurements on the human legs during locomotion showing almost no activity in the swing leg, except at the beginning and end of the swing phase, confirm this [3]. The first passive walkers were able to walk down a slope without any actuation and only using gravity to compensate for impact and friction losses [1]. By using compliant actuators these passive walkers can be made to walk on level ground. Compliant actuators are actuators that contain a physical elastic element, usually a spring. The elastic element is able to store and subsequently release energy, which benefits the present motor in the actuator. The compliance is, furthermore, capable of shock absorbance in contrast to stiff actuators. Incorporating compliant actuators into bipedal walkers is in accordance with the findings of Geyer *et al.* [4], namely that compliant legs are essential to explain human walking mechanics. The development of the Series Elastic Actuator (SEA) by Pratt [5] has been an important contribution in the research towards compliant actuators. Another compliant actuator, which is additionally capable of changing its compliance independent of equilibrium position, is the MACCEPA [6]. When optimizing the parameters of a MACCEPA to follow the torque profile of a human ankle, as measured by Winter [7], with minimum energy consumption the motor in the optimized MACCEPA only consumes 23% of the energy a stiff actuator would consume. The velocity and torque trajectory, and consequently the power trajectory, a stiff actuator would have to follow are the same as the Winter curves, so all black curves in Fig. 1 can be regarded as both the Winter data as the trajectories of a stiff actuator. The trajectories for the MACCEPA's motor are displayed as green dashed lines. As previously mentioned the MACCEPA is imposed to follow the Winter torque curve, however, as can be seen in Fig. 1, the velocity profile of the MACCEPA is lower than that of the stiff actuator and consequently the power requirements on the MACCEPA decrease. This is because of the spring storing and subsequently releasing energy. Due to the underlying principle of locomotion and the associated compliant actuators passive walkers are highly energy-efficient. A major drawback, however, is that they are designed for one specific walking motion, thus the number of possible motions is restricted.

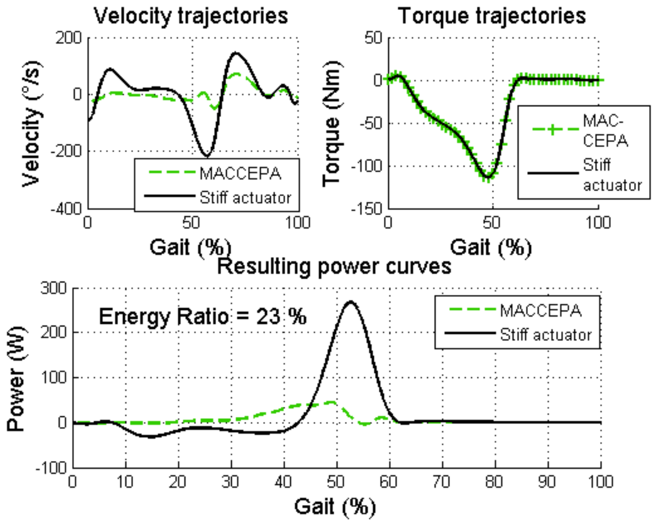

Figure 1. Velocity trajectories, torque trajectories, and resulting power curves for a MACCEPA and a stiff actuator when imposed to follow the torque profile of a human ankle (subject mass = 70kg) as provided by Winter [7].

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Although passive walkers can show an even higher energy-efficiency than human locomotion, they have yet to achieve the human versatility and robustness to dynamic environments, let alone those of active walkers. The challenge is finding an equilibrium between passive and active walkers that exhibits the best of both worlds, namely energy-efficiency, versatility, and robustness, as illustrated in Fig. 2.

II. COMPARING GAITS

The principle of humanlike locomotion, namely exploiting the natural motion of the legs, and the essential compliance of the legs is known. A methodology for quantifying the human likeness of gait for comparison between bipedal walkers and with the human counterpart is, however, yet to be developed. In the following paragraphs two means of comparing gaits, already discussed in literature, will be given.

A way of comparing the energy efficiency of mobile robots and humans is the specific cost of transport (c_t) [8], defined as the ratio of the energy consumed and the weight times the distance travelled:

$$c_t = \frac{E}{Mgd}. \tag{1}$$

With E the energy consumed, M the mass, g the gravitational constant, and d the distance travelled. To isolate the effectiveness of the mechanical design and controller from the efficiency of the actuators a distinction between specific energetic cost of transport (c_{et}) and specific mechanical cost of transport (c_{mt}) can be made. The specific energetic cost of transport comprises the total energy consumed, i.e. by electronics, microcontroller, and actuators, while the specific mechanical cost of transport only considers the positive mechanical work of the actuators [8].

The Froude number (Fr) was originally defined to compare the dynamics of ships that are geometrically similar in terms of wave resistance. Ships of similar shape are dynamically similar when the ratio of their velocity squared to their hull's length is equal [9]. It is defined as:

$$\mathrm{Fr} = \frac{v^2}{gl}. \tag{2}$$

Where v is the speed, l is the characteristic length (hip height for locomotion), and g is the gravitational constant.

Alexander postulated a dynamic similarity hypothesis for animals containing 5 criteria for dynamic similarity [10]:

- Each leg has the same phase relationship.
- Corresponding feet have equal duty factors.
- Relative (i.e. dimensionless) stride lengths are equal.
- Forces on feet are equal multiples of body weight.
- Power outputs are proportional to body weight times speed.

The dynamic similarity hypothesis predicts that animals will tend to move in a dynamically similar fashion if their speeds are proportional to the square root of their leg lengths, meaning equal Fr. The hypothesis demands that the stride frequency is inverse proportional to the square root of the leg length. To move in a dynamically similar animals' stride length λ should be proportional to leg length. The hypothesis predicts that animals of different sizes will uses same relative stride lengths when travelling at the same Froude number and thus move in a dynamically similar fashion. This, however, is not universally correct [11]. The hypothesis predicts equal duty factors at any given Froude number, which is more successful than the prediction of equal relative stride length [11].

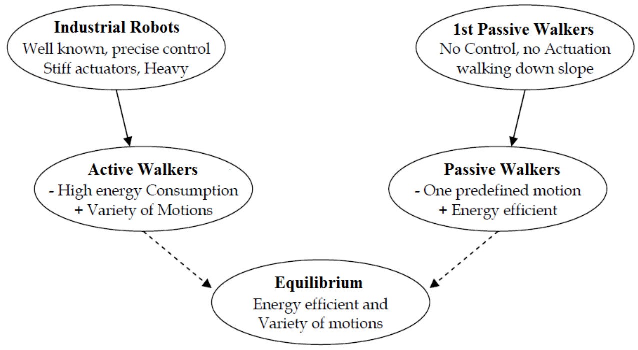

Figure 2. Towards an equilibrium combining positives of passive and active walkers for achieving humanlike locomotion.

ACKNOWLEDGMENT

This work has been funded by the European Commission 7th Framework Program as part of the project H_2R (no. 600698)

REFERENCES

[1] T. McGeer, "Passive dynamic walking," *The Int. J. of robotics Research*, vol. 9, no. 2, pp. 62 – 82, 1990.
[2] S. Mochon and T. McMahon, "Ballistic walking," *J. of Biomechanics*, vol. 13, no. 1, pp. 49 – 57, 1980.
[3] J. Basmajin and C. De Luca, "Muscle alive: Their functions revealed by electromyography," *Proc. of The Royal Society of Medicine*, vol. 278, p. 126, 1985.
[4] H. Geyer, A. Seyfarth, and R. Blickhan, "Compliant leg behavior explains basic dynamics of walking and running," *Proc. of The Royal Society B: Biological Sciences*, vol. 273, no. 1603, pp. 2861 – 2867, 2006.
[5] G.A. Pratt and M.M. Williamson, "Series elastic actuators," in *Human Robot Interaction and Cooperative Robots*, vol. 1 IEEE/RSJ, 1995, pp. 399 – 406.
[6] R. Van Ham, B. Vanderborght, M. Van Damme, B. Verrelst, and D. Lefeber, "MACCEPA, the mechanically adjustable compliance and controllable equilibrium position actuator: Design and implementation in a robot," *Robotics and Autonomous Systems*, vol. 55, no. 10, pp. 761 – 768, 2007.
[7] D. Winter, *The biomechanics and motor control of human gait: normal, elderly, and pathological.* University of Waterloo Press, 1991.
[8] S. Collins, A. Ruina, R. Tedrake, and M. Wisse, "Efficient bipedal robots based on passive-dynamic walkers," *Science*, vol. 307, pp. 1082 – 1085, Feb. 2005.
[9] C. Vaughan and M. O'Malley, "Froude and the contribution of naval architecture to our understanding of bipedal locomotion," *Gait & Posture*, vol. 21, no. 3, pp. 350 – 362, 2005.
[10] R.M. Alexander and A.S. Jayes, "A dynamic similarity hypothesis for the gaits of quadruped mammals," *J. of Zoology*, vol. 201, no. 1, pp. 135 – 152, 1983.
[11] R.M. Alexander, "The gaits of bipedal and quadruped animals," *The Int. J. of Robotics Research*, vol. 3, no. 2, pp. 49 -59, 1984.