Evaluating postural balance performance in exoskeleton robots

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***Abstract*— If a benchmark or assessment of postural balance in robotic systems is to say something about their performance in a real life, unstructured environment, the insights, metrics and procedures from human oriented research disciplines should be taken into consideration, in order to properly address the complexity of the topic. This refers mainly to the fields of human motor control theory, clinical assessment, gait analysis, and posturography. In these procedures the functions or mechanisms realizing postural balance are mainly treated as a black box, although the subsystems (sensory systems, executive functions, musculoskeletal structure) and sub-performances (anticipation, recovery, and reaction time) are taken into account and sometimes considered separately.**

I. Introduction

In recent years, an increasing number of exoskeletons for the legs have appeared in research as well as entered the market [1,2]. These robots are intended to support their human user in normal leg tasks, such as standing and walking.

Typical applications, foreseen for leg exoskeletons are:

- Worker support: to support a healthy user with a specific task, such as load carrying
- Rehabilitation training: to train patients with neurological damage during short sessions
- Assistive device: to assist healthy, frail or impaired users to extend their walking capacities in an all-day life environment

In worker support (currently mostly military) applications, the available exoskeletons focus on increasing the user capability to carry heavier loads over longer distances. Those for rehabilitation focus on making single steps, including the stance leg function to support the body weight and transporting the trunk, and the swing leg function to move the foot forward. In both functions, available exoskeletons do not support maintaining the postural balance. Most exoskeletons indeed make maintaining postural balance harder for their user [3].

In case of healthy users the balancing function is currently left to the user, that decides when and where to place the foot, and in case of impaired users, in rehabilitative or assistive use, additional support is used for stabilization of posture, such as an overhead weight support system, the use of crutches or the continuous support of a therapist.

For this reason one of the current topics in exoskeleton research and development is how to make an exoskeleton support the postural balance of the user during walking, standing, sit to stand transitions and similar functional tasks (for example www.balance-fp7.eu).

II. Postural Balance Control in Exoskeletons

A. *Postural Balance Control*

While performing activities like walking, standing or standing-up, humans aim at moving the body's center of mass (CoM) in a desired direction or keeping it in a safe and stable location. This requires controlling the forces that act on the CoM. These forces can be generated through **leg joint torques**, through **upper body and limb motions** or by changing **the locations of the feet relative to the CoM**. Such balance related strategies can be supported by an exoskeleton. Especially suitable to be supported by a leg exoskeleton are the adaptation of the joint stiffnesses (or virtual leg stiffness) and the adequate feet placements.

In the configuration of a human wearing an exoskeleton, both the human and exoskeleton are acting (each of them with their strength and limitation) toward the same objective: performing efficiently (execution time, energy) and safely (without falling) a functional task. However, due to different strategies, it might be the case that both entities are not performing coherent and constructive actions, generating overall system perturbations that can be threatening for the user.

With these considerations comes the question how to benchmark, assess or evaluate the performance of exoskeletons regarding postural balance control. In this abstract we shortly review the way postural balance performance is considered in the fields related to human motor control, biomechanics and neurorehabilitation [4,5,6,7,8,9], in order to find inspiration in developing methods that can be used to assessing or benchmarking exoskeletons (and additionally also in autonomous bipedal robots).

B. *Background from human motor control*

Important insights regarding balance from human oriented fields of research are listed here as a number of statements, that are important to consider also in evaluating performance of robotic devices:

- **Postural stability** (also referred to as **balance**) is the ability to **control the center of mass (CoM) in relationship to the base of support (BoS)**. It can

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be represented by the interaction between CoM and Center of Pressure (CoP) [4]

- **Postural control requirements vary with task and environment**. E.g. the task of controlling stability during walking is very different from the task of balance during stance. [4]
- Postural balance control involves **maintaining posture, facilitating movement,** and **recovering equilibrium** [5]
- A variety of balance control systems (**reactive, anticipatory, sensory, dynamic, and limits of stability**) and physiological systems (**vestibular, visual, proprioceptive, muscle strength, and reaction time**) contribute to balance [5]

These few statements already make clear that no simple procedure will be sufficient to adequately assess or benchmark "postural stability performance" in neither human, exoskeleton (human+machine) nor robotic bipeds. This is especially valid if a benchmark is to say something about performance in a real world environment carrying out real functional tasks, and not only to make an 'academic' comparison between devices on a specific but necessarily limited model task.

For example, the tests that are often used in theoretical analyses, where an obstacle or lowering of the floor is introduced in the line of straight walking (such as the Gait Sensitivity Norm [10]), in order to see if a walker (model) after the interaction either returns to a stable gait cycle – or falls over, or for example by computing the distance of the actual Zero Moment Point (ZMP) to some set ZMP reference trajectory, or limit-cycle based approaches like Poincaré-maps, by no means cover the complexity of postural balance in a common all day life environment, and at best could be one among several elements of a benchmark.

In postural balance the normal, or rather the critical condition, is the irregular, in the sense that normal straight walking is not the critical condition, but rather: starting, turning, changing speed, stepping up, carrying weights, being perturbed, stopping, and so on.

III. Example of Assessment of Postural Balance Performance

A good example of an extended assessment can be found in the "BESTest", a clinical procedure that explicitly addresses the full complexity and involved subsystems of postural balance [6]. This procedure is developed to assess postural balance in a way that would give an indication of underlying causes of malfunctioning. The BESTest consists of 36 items, grouped into 6 systems:

- Biomechanical Constraints,
- Stability Limits/Verticality,
- Anticipatory Postural Adjustments,
- Postural Responses,
- Sensory Orientation, and
- Stability in Gait.

In order to make such a test useful for the area of robotics, it is important to quantify the procedures as much as possible, and to indicate which parameters during such procedures should be recorded. It seems essential to at least always record the movement of the Center of Mass as well as the Base of Support and the Center of Pressure, as these are the core components of postural balance control. Additionally, quantitative information about perturbations, obstacles and floor properties should be available in order to have a reproducible procedure. If the target is to realize a limited benchmark procedure, it might be adequate to make a benchmark walking circuit, which contains all essential, relevant and feasible elements from a test like the BESTest. In such a case it could be sufficient to record how often the robot has fallen over, or needed some kind of emergency intervention.

IV. Conclusion

If a benchmark or assessment of postural balance in robotic systems is to say something about their performance in a real, unstructured environment, the insights, metrics and procedures from human oriented research disciplines should be taken into consideration, in order to properly address the complexity of the topic. This refers mainly to the fields of human motor control theory, clinical assessment, gait analysis, and posturography [4,5,6,7,8,9]. These methods typically evaluate the ability to maintain postural balance, as is relevant to all day tasks and all day environments. In these procedures the functions or mechanisms realizing postural balance are mainly treated as a black box, although the subsystems (sensory systems, executive functions, musculoskeletal structure) and sub-performances (anticipation, recovery, reaction time) are taken into account and sometimes considered separately.

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