Erschienen in: Biomimetic and Biohybrid Systems : Third International Conference, Living Machines 2014, Milan, Italy, July 30 – August 1, 2014 ; Proceedings / Duff, Armin (Hrsg.). - Cham : Springer, 2014. - (Lecture notes in computer science ; 8608). - S. 320-331. - ISBN 978-3-319-09435-9
https://dx.doi.org/10.1007/978-3-319-09435-9_28

Benchmarking Human-Like Posture and Locomotion of Humanoid Robots: A Preliminary Scheme

Diego Torricelli[1], Rahman S.M. Mizanoor [2], Jose Gonzalez[3], Vittorio Lippi[4],
Georg Hettich[4], Lorenz Asslaender[4], Maarten Weckx[3], Bram Vanderborght[3],
Strahinja Dosen[5], Massimo Sartori[5], Jie Zhao[6], Steffen Schütz[6],
Qi Liu[6], Thomas Mergner[4], Dirk Lefeber[3], Dario Farina[5], Karsten Berns[6],
and Jose Louis Pons[1]

[1] Bioengineering Group, Spanish National Research Center (CSIC), Madrid, Spain
`diego.torricelli@csic.es`
[2] Department of Mechanical Engineering, Vrije Universiteit Brussel, Belgium
`mizanoor.rahman@vub.ac.be`
[3] Technaid S.L., Madrid, Spain
`jose.gonzalez@technaid.com`
[4] Neurology, University of Freiburg, Neurozentrum, Freiburg, Germany
`vittorio.lippi@uniklinik-freiburg.de`
[5] University Medical Center Göttingen, Germany
`strahinja.dosen@bccn.uni-goettingen.de`
[6] Robotics Research Lab, University of Kaiserslautern, Germany
`zhao@cs.uni-kl.de`

Abstract. The difficulty in defining standard benchmarks for human likeness is a well-known problem in bipedal robotics. This paper proposes the conceptual design of a novel benchmarking scheme for bipedal robots based on existing criteria and benchmarks related to the sensorimotor mechanisms involved in human walking and posture. The proposed scheme aims to be sufficiently generic to permit its application to a wide range of bipedal platforms, and sufficiently specific to rigorously test the sensorimotor skills found in humans.

The achievement of global consensus on the definition of human likeness has a crucial importance not only in the field of humanoid robotics, but also in neuroscience and clinical settings. The EU project H2R is specifically dealing with this problem. A preliminary solution is here given to encourage the international discussion on this topic within the scientific community.

Keywords: Benchmarking, human likeness, bipedal robots, walking, standing, posture.

1 Introduction

The issue of benchmarking robotic locomotion has been receiving increasing attention during the last decade [1, 2]. The use of benchmarks may help standardize the robot designs and fabrication, ease the evaluation and comparison of the systems, and exploit the biological solutions for many unsolved problems such as the mechanical compliance, energy consumption and enhanced human-robot interactions.

The main obstacle in identifying common benchmarks is that different methods and metrics are typically employed and reported for specific robotic systems and functional scenarios [1]. In the field of humanoid robots, the benchmarks previously proposed either focus only on the result of a specific task (e.g. open a door, stair climbing, [3]) or on specific problems related to intelligence (e.g. social and multi-agent interactions, [4]).

Stable locomotion represents one of the main challenges in humanoid robotics for which no well-defined standards and benchmarking schemes exist. Despite their potential for high mobility, most bipeds have never been tested outside the laboratory. The problem is mainly due to the fact that the control and mechatronics of a legged machine is intrinsically a complex issue and its evaluation and comparison is very difficult. Human likeness is considered a significant criterion for design excellence, under the perspective of smoothness, versatility and energy efficiency [5]. However, a generalized, well-accepted and complete benchmarking scheme of human-like locomotion is not yet available.

Within the EU project H2R [6], we are promoting the international discussion on the features to be included in the ideal benchmarking scheme. As a first step towards this goal, we are presenting a conceptual design of a benchmarking scheme for human-like walking and standing. The proposed scheme has a twofold goal. On the one hand it aims to be sufficiently generic and versatile to permit its application to a wide range of bipedal platforms and scenarios. On the other hand, it should be sufficiently specific to rigorously test the sensorimotor skills found in humans. We specifically omitted arm, articulated spine and head movements, although they can implicitly influence gait and postural behaviors.

2 The Proposed Benchmarking Scheme

2.1 General Concepts

Our goal is to identify a subset of the possible human-like features related to walking and standing, which are applicable to different robotic bipedal platforms, regardless of their weight, size, number of degrees of freedom, or control architecture. This proposal is limited to those features related to sensorimotor control. High-level cognitive abilities, such as path planning, prediction, external world recognition, and learning, are not included in this scheme.

To standardize a method for the evaluation of the different human-like features in the different domains, we propose a benchmarking scheme that is schematically resumed in Table 1 and Table 2. Each scheme is structured in three main sections:

A. *Sensorimotor tasks*. In this part, the benchmarking scheme reports the internal and external constraints of the problem, meaning the desired motor task (e.g. standing, walking), and the interaction with the external world (e.g. pushes, inclined surface, etc.). We refer to this as to sensorimotor tasks because they underlie feedback propagation and processing of somatosensory information including joint internal forces and whole-body position.

B. *Benchmarking criteria.* It includes the specific sensorimotor abilities to be measured (e.g. robustness, energy consumption) and the different benchmarks that are used to quantify them (e.g. speed, falling rate, etc.).
C. *Perturbation devices.* This third part includes possible external perturbation devices that can be used in a laboratory setting to further measure the benchmarks proposed in the previous part (item B).

2.2 Benchmarking Scheme for Standing

Posture control is the ability to maintain body center of mass (CoM) above the base of support, compensating external disturbances such as gravity, pushes or support surface movements. Posture control deficits severely affect walking performance. For this reason, testing postural skills has high relevance for the assessment of locomotion abilities, both in humans and robotic scenarios [7, 8]. Postural skills in humans are normally assessed by analyzing the excursion of center of pressure (CoP) and center of mass (CoM). Also kinematics and intersegmental forces can be measured by applying motion analysis techniques and mechanical modeling [9].

In this section, we present a number of methods and criteria that have been used either in human studies or in robotic scenarios, to measure the postural control ability of a bipedal structure. Among all the methods identified in the literature, we selected those that in our opinion are particularly suitable to reveal human-like features (Table 1).

Sensorimotor Tasks

We identified three relevant sensorimotor scenarios (see Table 1A): i) unperturbed standing, ii) perturbed standing, and iii) voluntary CoM displacements.

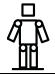
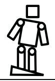
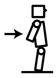
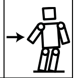
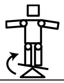
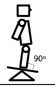
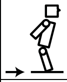
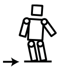
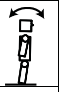
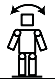
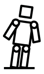
Unperturbed standing is normally assessed on static horizontal or inclined support surface. The inclination of the surface can be in the anterio-posterior direction (sagittal plane) or in the medio-lateral direction (frontal plane).

In the case of perturbed standing, the main proposed perturbations will be (a) pushes, (b) support surface tilts, and (c) support surface translations. Within the tilting perturbations, the body sway referenced platform (BSRP) mode is a useful technique to eliminate ankle proprioceptive feedback and selectively test the vestibular system in the absence of vision [10]. The directions of disturbances are distinguished in sagittal plane and frontal plane, except for BSRP mode, which is limited to sagittal plane due to ankle morphology.

Concerning voluntary movements, a typical test that we consider useful is the rhythmic weight shift (RWS). It is already used in clinical scenarios, and consists of performing sinusoidal rhythmic sways with different amplitudes and frequencies in sagittal and lateral directions [11]. Another test that should be considered is the maximum static leaning. This test is also used in clinical settings, under the name of Limits of Stability (LOS) test [12].

Table 1. The proposed benchmarking scheme for standing

A. Sensorimotor tasks

Motor task	Condition	Direction	
Unperturbed	Horizontal surface	-	
	Inclined surface	Sagittal	
		Lateral	
Perturbed	Pushes	Sagittal	
		Lateral	
	Surface tilt	Sagittal	
		Lateral	
		Body sway reference platform (BSRP)	
	Surface translation	Sagittal	
		Lateral	
Voluntary movements	Rhythmic Weight Shift (RWS) test	Sagittal	
		Lateral	
	Limits of Stability (LOS) test	Sagittal	
		Lateral	

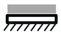
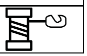
B. Benchmarking criteria

Feature	Criterion	Measurements tools		
		◁	↓	∠
Stability	Max support amplitude/ frequency	X		X
	Max external force	X	X	
	Max voluntary CoM displacement/frequency	X		X
	Energy Stability Margin (EMS)		X	X
	Time standing on BSRP	X		
Motion	Joint kinematics			X
	Frequency Response Function (FRF)		X	
	Compliance to external forces		X	X
	Ankle-hip coordination		X	X
	Natural looking motion	X		
Energy efficiency	Energy per DoF*		X	X
	Energy per weight-height*		X	X

◁ = Visual inspection, ↓ = Kinetics, ∠ = Kinematics

* To be further defined

C. Perturbation devices

Function	Typology		
Support	Fixed	Sloped board	
	Passive	Rubber foam	
		Wheel board	
		Rocker board	
	Actuated	Tilt	
		4-bar mechanism	
		Stuart platform	
Pushing	Manual		
	Falling ball		
	Rope and winch		

Benchmarking Criteria

In the proposed scheme, we identified the following features to evaluate human-like robotic behavior (Table 1B): i) stability, ii) motion, and iii) energy efficiency.

Stability can be defined as the ability to maintain balance without falling. Stability can be defined as the ability to maintain balance without falling. The maximum magnitudes of the disturbance/condition that the robot can handle before falling can be considered as a quantitative metrics of stability [13]. In particular, the following metrics are proposed: for perturbed scenario, maximum amplitude and frequency of disturbance (tilt or translation), and maximum external force (for push condition) can be used. For voluntary dynamic movements (RWS test), the maximum amplitude and frequency of CoM displacements is proposed. An accepted approach to identify the limits of stability is the Energy Stability Margin (ESM) proposed by Messuri & Klein [14] and its extensions [15, 16], which describe the minimal potential energy necessary to tumble the robot over one of the boundary edges of the support polygon. In the case of BSRP mode, a possible metric of stability is the time the robot is able to stand without falling.

Human-like (or natural looking) motion can be assessed directly – by comparing human and robot trajectories in the space of joint positions – or globally – by measuring whole body motion or the relative contribution of different body parts. Whole body motion can be accurately quantified using the frequency response function (FRF), which allows to characterize the gain and phase of CoM displacement in response to the, typically pseudorandom tilt disturbance [7, 17]. Visual inspection from human observers, using a dot motion display, has been proposed as an effective alternative way to characterize human-like motion from a global perspective [18].

In human postural tasks, ankle and hip move coordinately to keep the CoM over the base of support. The relative contribution of hip and ankle strategy changes with the magnitudes and typology of the disturbance [13], as well as with age and sensory impairments. An appropriate quantification of this inter-joint coordination can be obtained by correlating sways during sine wave stimulus, as done in [19]. Humans are also characterized by compliant behavior, emerging in response to interactions with the environment and to external disturbances. We propose to estimate compliance during standing by measuring the CoM displacements in consequence of external pushes.

Balancing of upright stance in humans is a continuously active process, which therefore requires energy [20]. However, to our best knowledge, assessing energy costs during standing is not explicitly considered in bipedal robotics. We believe that efficiency should be taken into account in the ideal benchmarking scheme for standing, in particular during perturbed conditions. In this direction, a reasonable solution may be to adapt some of the methods commonly used for walking, such as the energy-per-DoF or the energy-per-height/weight (see Section 2.3).

Perturbation Devices

Perturbation devices may introduce important constraints in the application of benchmarking procedures, thus biasing the comparison between robots. We propose a number of solutions that can be implemented in most laboratory settings (Table 1C).

Support surface devices are classified in fixed and moving. Moving devices are distinguished in actuated (by motors or manually) and passive. Among the passive solutions, a rubber foam can be used to induce effective tilting disturbances, as it is currently done in clinical setting. A wheel board can be used to induce translational disturbances. The rocker board is an interesting solution that combines tilt perturbations and translations. Even if very simple, this condition is very challenging for robotic control systems. An effective device for translations is a parallel swing mechanism attached to the roof. Complex conditions like 3D or pseudorandom surface movements should be induced by a motion platform, often in the form of a Stuart platform. Finally, pushing disturbances could be performed manually by a swinging ball of known weight and release height, or by a rope and winch.

Safety mechanisms should be used in all scenarios to avoid robot breaking after falling. A simple rope attached to the roof, or similar solution, should be sufficient.

2.3 Benchmarking Scheme for Walking

Achieving stable and efficient walking is a crucial goal in humanoid design. In humans, walking emerges from the combination of several mechanisms, which include neural, biomechanical and morphological aspects [21]. As a result humans show very robust, versatile and energy efficient functional abilities in a vast range of conditions. It is generally believed that translating such human-like principles into robotic platforms may improve their functional performance. In human studies, huge quantitative information on limb kinematics and kinetics has been collected over the last century, and several metrics have been derived from it. Among these, we selected appropriate candidates that can describe typical human behavior and that can be easily applied to the robotic scenario. Results are depicted in Table 2.

Sensorimotor Tasks

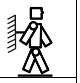
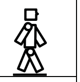
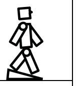
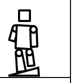
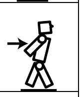
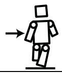
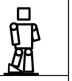
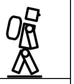
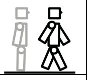
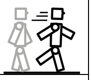
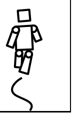
Walking tasks are organized in three classes (Table 2A): unperturbed walking, perturbed walking, and more complex voluntary motion. In the unperturbed domain, horizontal flat walking with body weight support (BWS) is convenient to test rhythmic leg movements separately from balance. If BWS is removed, free over-ground walking is obtained, where all the basic functions of locomotion can be tested. Presence of slopes has been also included within the unperturbed scenario, because no changes in the environment occur. Three kinds of slopes have been included: upward, downward, and lateral.

Four perturbed scenarios are considered: pushes, rough terrain, changes in slope and weight bearing, in sagittal and lateral direction. In the weight-bearing scenario, the condition of transporting a backpack of unknown weight is considered.

The last class of benchmarking scenario is related to voluntary changes of locomotion parameters. Three cases will be considered. The first one is changing from standing to walking, and vice versa. This condition involves complex coordination, such as shifting body weight to one foot, inclining the upper body, and taking the first step. The second task is the online change of walking speed. The third voluntary task is to change direction during locomotion.

Table 2. The proposed benchmarking scheme for walking

A. Sensorimotor tasks

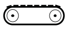
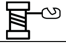
Motor task	**External condition**	**Direction**	
Unperturbed walking	Flat ground, with BWS	-	
	Flat ground	-	
	Continuous Slopes	Up	
		Down	
		Lateral	
Perturbed walking	Pushes	Sagittal	
		Lateral	
	Rough terrain	Sagittal	
		Lateral	
	Change slope	Sagittal	
	Weight bearing		
Voluntary transitions	Start-stop walking	-	
	Change speed	-	
	Curved path	-	

B. Benchmarking criteria

Feature		**Criterion**	**Measures**		
			👁	⤓	∠
Stability		Max and min speed	X		X
		Max number of steps	X		
		Max slope	X		X
		Max ext. force	X	X	
		Max obstacles dimension	X		
		Max ground softness	X		
		Max load	X		
		Max centrifugal force	X		X
		Success rate of transitions	X		
Motion		Kinematic profiles			X
		Gait harmony		X	X
		Dynamic Time Warping			X
		Heel, ankle, forefoot rocker			X
		Natural looking motion	X		
		Compliance to ext. forces	X	X	X
	DYNAMIC SIMILARITY	Equal relative foot phase			X
		Equal duty factor			X
		Equal Froude number			X
Kinetics		Equal force on foot		X	X
		Power prop. m*v		X	X
		Joint moments profiles		X	X
		Passive Gait Measure (PGM)		X	X
		Dynamic Gait Measure (DGM)		X	X
Energy efficiency		Spec energy cost transp. C_{et}		X	X
		Spec mech. cost transp. C_{mt}		X	X
		Energy per DoF		X	X

👁 = Visual inspection, ⤓ = Kinetics, ∠ = Kinematics

C. Perturbation devices

Function	**Typology**		
Terrain	Clear	Static slope	
		Treadmill	
	Irregular	Hard & continuous	
		Soft & continuous	
		Sparse obstacles	
Pushing	Manual		
	Falling ball		
	Rope and winch		

Benchmarking Criteria

Stability. The most general criterion for robot (and human) stability is the robustness to falling. The condition of "falling" is easily detectable by visual inspection. As done in standing, to convert this discrete criterion into quantitative metrics, the maximum magnitudes of the disturbance/condition that the robot can handle before falling will be considered. For all walking conditions, the maximum and minimum speed, as well as the maximum number of steps before falling can be used. In more specific scenarios, the following metrics can be defined: for walking on slopes, the maximum ground inclination allowed; for pushes, the maximum external force tolerated by the biped during single- and double-stance phases; for irregular terrain, the maximum obstacle dimension, and in the case of soft terrain, the maximum ground softness; in weight bearing condition, the maximum permitted loading; in the case of curved path, an indicator of the maximum centrifugal force, e.g. the ratio between speed and radius of curvature. For voluntary transitions, stability can be hardly quantified on a continuous scale, because these can be either performed or not during a single trial. For this reason, we propose to measure the success rate of achievement across a fixed amount of trials.

Kinematic Analysis. At the kinematic level, the basic procedure to compare robots with human is direct correlation of joint kinematic profiles. In particular, knee bending, pelvis movements and foot placement seem to be strong indicators of human likeness. On a more global level, the gait harmony has been proposed as a metric to measure the synchrony and symmetry of whole-body gait movements [22], obtained by either spatiotemporal parameters or acceleration harmonics of the CoM. A further good candidate for comparing kinematics across robots and humans is the Dynamic Time Warping (DTW) method [23], which measures the similarity between temporal sequences that vary in time or speed. It is typically applied in speech recognition, and no application to walking has been found in literature. Foot motion is also a crucial aspect in walking. In the ideal benchmarking scheme, the assessment of basic wheel-like mechanisms of the foot - namely heel, ankle, and forefoot rockers – should be included [24, 25]. An alternative way to evaluate human-like motion is by visual inspection using the dot motion display, as discussed in the section on standing. Alexander [26] postulated five criteria to assess dynamic similarity across bipeds of any size. Three of these criteria concern motion: I) equal contralateral relative foot phase, which measures the symmetry of movement, II) equal duty factor, which indicates the percentage of stance phase within a gait cycle, and III) equal Froude number [27]. Previous described methods are normally applied during unperturbed conditions. Perturbed scenario may also be useful to test one typical feature of human motion: compliance to external disturbances. To our knowledge, no well-defined methods have been proposed in literature to quantify how the compliant characteristics of the human body affect the reaction to unexpected forces.

Kinetic Analysis. Human locomotion is characterized by passive and active dynamic behaviors interspersed throughout a gait cycle. A classic approach to analyze kinetics is to measure and then compare the joint moment profiles. Recently, the Passive Gait Measure (PGM) and Dynamic Gait Measure (DGM) have been proposed to quantify the passive and dynamic characteristics of human-like locomotion [28]. Internal and external forces in human walking are repeatable variables, which could be used as gold standards for comparison with humanoid counterparts. Alexander also postulated two criteria for dynamic similar gaits concerning forces, in addition to the previous three motion-based criteria: IV) forces on feet are equal multiples of body weight; and V) power outputs are proportional to body weight times speed.

Energy Efficiency. Energy consumption is one of the most important factors that mark the difference between humans and robots. A widely used benchmark of walking efficiency is the specific cost of transport (c_t) [5, 29], defined as the ratio of the energy consumed and the weight times the distance travelled. The specific energetic cost of transport comprises the total energy consumed, including positive and negative work of actuators and energy costs related to electronics. The specific *mechanical* cost of transport (c_{mt}) is needed when one wants to isolate the positive mechanical work, and more reliably compare the energy costs of different robotic platforms independently from the control aspects. As an application example, the specific costs of transport of three robots compared to human values were reported in [5]. Energy and power consumption can be also measured at joint level, by measuring torques and joint speeds.

Perturbation Devices

A successful benchmarking scheme should be easily applicable to different platforms and laboratory scenarios. To this aim, we propose some practical solutions, taking into account that perturbations should be applied in a wide range of magnitudes and timing, and that the device should be easy to use, as low cost as possible, and possibly available in the market.

In the case of inclined walking, the sagittal slope can be reproduced by a static support (e.g. wooden) or by an off-the-shelf inclined treadmill. For lateral slopes, the static support may be the preferred solution. The perturbation device should allow for inclinations up to at least 10º upwards and downwards.

Possible solutions for pushing disturbances are a pendulum made of a known mass released from a predefined height, or a rope connected to a sensorised winch, similarly to what proposed in standing condition. In both cases, the robot should be placed on a treadmill, since both ball and rope should be conveniently attached to static supports. Also manual pushes can be considered, which may allow for a very fast and easy to use test, yet more difficult to measure in a quantitative way.

Reproducing rough terrain should take into account the following variables: i) dimension of the obstacle with respect to the dimension of the biped, ii) shape of the obstacle (e.g. presence of inclined surfaces), iii) rigidity of the obstacle (hard or soft), iv) number of obstacles, and v) distance between obstacles. Among the infinite possible combinations of these variables, we propose three different scenarios: 1) continuous irregular terrain, to test the capability of the ankle to adapt to the terrain during the weight acceptance; 2) continuous soft terrain, to test the ability to maintain balance and generate propulsion, and 3) sparse obstacles located on the ground, to test the reaction to collisions and unexpected deviations of limb motion.

3 Discussion

With respect to current benchmarking in robotic competitions – e.g. DARPA robotic challenge and Robocup - this scheme represents a complementary tool specifically focused on human-like behavior rather than absolute performance. In this respect, it is worth mentioning that higher human likeness does not necessarily mean higher functional or stability performance. For instance, during standing, robots could easily outperform human performance in terms of stability. Conversely, during walking, achieving human like performance would translate into increased stability, versatility and efficiency. Another relevant advantage with respect to competition contexts is that testing specific sensorimotor functions instead of global behavior may constitute a useful approach to better identify specific cause-effect relationships.

The development of this benchmarking scheme is still at a very early stage. With this paper we want to provide a robust and generic benchmarking structure as well as stimulate the international discussion on the relevant features and methods to be included. As a practical effort in this direction, we are currently developing an open source software that will be disseminated in the near future within the robotics community. The software is made of two parts. In the first part, the user can select the motor tasks to test, as well as the limitations on measurement/perturbation technology available in the laboratory. With these inputs, the software will define the type of benchmarks that can be applied to the robotic platform. The second part of the software allows calculating and reporting the benchmark values obtained by the particular robot, and store the data used to obtain these results. The first release of this software will also serve as a beta-test for the evaluation of usability across different laboratory contexts. Through a web-based application, feedback from users will be collected on the following issues: i) relevance of the proposed benchmarks, ii) usability of the software, and iii) ideas for improvements, e.g. new benchmarks, protocols, or devices. The user will also have the opportunity to share the values obtained by the specific robot. These data will be useful to start building appropriate scales for the correct evaluation of human likeness, through the comparison with values obtained by other laboratories and by human experiments in the same conditions. A mailing list has been already created [6] to collect ideas and disseminate events specifically focused on this topic.

Further efforts should be devoted to define the actual reference values necessary to develop meaningful quantitative scales. The general rationale is to assume the human behavior as golden standard, namely 100% human-like. Appropriate database of human data in all conditions should thus be made available. The generation of human data not available yet may constitute an interesting goal for human experimental research. An additional open issue is the definition of disturbance magnitudes, which should be appropriately scaled – according to the existing scaling laws [30] – to allow its usage across bipeds with different sizes and weights.

In this paper, we did not include an extensive analysis of the state of the art of current benchmarking methods, due to space limitations. This will be possibly included in a further extended publication, and used to propose first guess estimations on quantitative reference ranges.

4 Conclusion

We believe that benchmarking human-like posture and locomotion is a major challenge and unresolved key issue for humanoid robotics. The major goal of our efforts is to produce a benchmarking solution that can be realistically used by most research groups around the world. For this reason, we propose a scheme based on a modular structure, which can permit to select the subgroups of conditions, benchmarks and devices that are more suitable to the specific robotic platform and laboratory setting.

Future efforts should be devoted to: i) the inclusion of new ideas for benchmarks and metrics arising from the community, ii) the definition of a minimum subset of benchmarks among all proposed, iii) the establishment of a reference database of human data for all conditions, iv) the definition of absolute ranges of all metrics proposed. To facilitate this process, the H2R project is currently developing an open source software that will be soon shared within the international community.

Acknowledgements. The research activity presented in this paper has been funded by the European Seventh Framework Programme FP7-ICT-2011-9, under the grant agreement no 60069 - H2R “Integrative Approach for the Emergence of Human-like Robot Locomotion”.

References

1. Behnke, S.: Robot Competitions Ideal Benchmarks for Robotics Research. In: IROS 2006 - Workshop on Benchmarks in Robotics Research (2006)
2. del Pôbil, P.: A.: Why do We Need Benchmarks in Robotics Research? In: IROS2006 - Workshop on Benchmarks in Robotics Research (2006)
3. DARPA Robotics Challenge Trials (DRC), `http://www.theroboticschallenge.org/`
4. Rahman, S.M.M.: Evaluating and Benchmarking the Interactions between a Humanoid Robot and a Virtual Human for a Real-World Social Task. In: Papasratorn, B., Charoenkitkarn, N., Vanijja, V., Chongsuphajaisiddhi, V. (eds.) IAIT 2013. CCIS, vol. 409, pp. 184–197. Springer, Heidelberg (2013)
5. Collins, S., Ruina, A., Tedrake, R., Wisse, M.: Efficient bipedal robots based on passive-dynamic walkers. Science 307, 1082–1085 (2005)
6. H2R, Integrative approach for the emergence of human-like locomotion, FP7-ICT-2011-9 Agreement no60069, `http://www.h2rproject.eu`
7. Peterka, R.J.: Sensorimotor integration in human postural control. J. Neurophysiol. 88, 1097–1118 (2002)
8. Mergner, T., Schweigart, G., Fennell, L.: Vestibular humanoid postural control. J. Physiol. Paris 103, 178–194 (2009)
9. Winter, D.A.: Biomechanics and motor control of human gait: normal, elderly and pathological (1991)
10. Ishida, A., Imai, S., Fukuoka, Y.: Analysis of the posture control system under fixed and sway-referenced support conditions. IEEE Trans. Biomed. Eng. 44, 331–336 (1997)
11. Cheng, P.-T., Wang, C.-M., Chung, C.-Y., Chen, C.-L.: Effects of visual feedback rhythmic weight-shift training on hemiplegic stroke patients. Clin. Rehabil. 18, 747–753 (2004)

12. Wallmann, H.W.: Comparison of elderly nonfallers and fallers on performance measures of functional reach, sensory organization, and limits of stability. J. Gerontol. A. Biol. Sci. Med. Sci. 56, M580–M583 (2001)
13. Horak, F., Macpherson, J.: Postural orientation and equilibrium. Compr. Physiol. (1996)
14. Messuri, D., Klein, C.: Automatic body regulation for maintaining stability of a legged vehicle during rough-terrain locomotion. IEEE J. Robot. Autom. 1 (1985)
15. Lin, B.-S., Song, S.-M.: Dynamic modeling, stability and energy efficiency of a quadrupedal walking machine. In: Proc. IEEE Int. Conf. Robot. Autom. (1993)
16. Hirose, S., Tsukagoshi, H., Yoneda, K.: Normalized energy stability margin and its contour of walking vehicles on rough terrain. In: Proc. 2001 ICRA. IEEE Int. Conf. Robot. Autom (Cat. No.01CH37164), vol. 1 (2001)
17. Goodworth, A.D., Peterka, R.J.: Contribution of sensorimotor integration to spinal stabilization in humans. J. Neurophysiol. 102, 496–512 (2009)
18. Troje, N.F.: Decomposing biological motion: a framework for analysis and synthesis of human gait patterns. J. Vis. 2, 371–387 (2002)
19. Schweigart, G., Mergner, T.: Human stance control beyond steady state response and inverted pendulum simplification. Exp. Brain Res. 185, 635–653 (2008)
20. Miles-Chan, J.L., Sarafian, D., Montani, J.-P., Schutz, Y., Dulloo, A.: Heterogeneity in the energy cost of posture maintenance during standing relative to sitting: phenotyping according to magnitude and time-course. PLoS One 8, e65827 (2013)
21. Bernstein, N.A.: Dexterity and its development (1996)
22. Iosa, M., Fusco, A., Marchetti, F., Morone, G., Caltagirone, C., Paolucci, S., Peppe, A.: The golden ratio of gait harmony: repetitive proportions of repetitive gait phases. Biomed Res. Int. 2013, 918642 (2013)
23. Lemire, D.: Faster retrieval with a two-pass dynamic-time-warping lower bound. Pattern Recognit. 42, 2169–2180 (2009)
24. Perry, J.: Gait analysis: normal and pathological function. SLACK Inc. (1992)
25. Hansen, A.H., Childress, D.S., Knox, E.H.: Roll-over shapes of human locomotor systems: effects of walking speed. Clin. Biomech. 19, 407–414 (2004)
26. Alexander, R.M.: The Gaits of Bipedal and Quadrupedal Animals. Int. J. Rob. Res. 3, 49–59 (1984)
27. Duncan, W.J.: Physical similarity and dimensional analysis, London (1957)
28. Mummolo, C., Kim, J.H.: Passive and dynamic gait measures for biped mechanism: formulation and simulation analysis. Robotica 31, 555–572 (2012)
29. Gabrielli, G., von Kármán, T.: What price speed? Specific power required for propulsion of vehicles. Mech. Eng. ASME 72, 775–781 (1950)
30. Dermitzakis, K., Carbajal, J.P., Marden, J.H.: Scaling laws in robotics. Procedia Computer Science, 250–252 (2011)