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Benchmarking the HRP-2 humanoid robot during locomotion

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2 ABSTRACT

In this paper we report results from a campaign of measurement in a laboratory allowing to put a humanoid robot HRP-2 in a controlled environment. We have investigated the effect of temperature variations on the robot capabilities to walk. In order to benchmark various motions modalities and algorithms we computed a set of performance indicators for bipedal locomotion. The scope of the algorithms for motion generation evaluated here is rather large as it spans analytical solutions to numerical optimization approaches able to realize real-time walking or multi-contacts.

10 **Keywords:** benchmarking, bipedal locomotion, humanoid robot HRP-2, controlled environment, numerical optimization, walking

1 INTRODUCTION



Figure 1. General architecture to generate motion for a humanoid robot. In this paper the boxes in orange are the one benchmarked, whereas the blue boxes are not benchmarked

11 From the seminal work of Chestnutt (2010) to the recent methods proposed in the frame of the Darpa
 12 Robotics Challenge (DRC) Tsagarakis et al. (2017); Lim et al. (2017); Radford et al. (2015); Johnson
 13 et al. (2017); Marion et al. (2017); DeDonato et al. (2017), humanoid robots are moving using a control
 14 architecture following the general framework depicted in Fig. 1. Based on an internal representation of
 15 the environment and the localization of the robot (\hat{r}_b and $\hat{\theta}_b$ being respectively the base position and
 16 orientation), the **Motion Planner (MP)** plans a sequence of reference end-effector contact positions (f^{ref}),
 17 or a reference center of mass linear velocity combined with a reference waist angular velocity (V^{ref}).
 18 These references are then provided to a **Model-Predictive Whole-Body Controller (MPWBC)** which
 19 generates a motor command for each joint (joint torques (τ^{ref}), positions (q^{ref}), velocities (\dot{q}^{ref}) and
 20 accelerations (\ddot{q}^{ref})). This block is critical in terms of safety as it maintains the dynamics feasibility of
 21 the control and the balance of the robot. The **Model-Predictive Whole-Body Controller (WBC)** can be
 22 expressed as a unique optimal control problem but at the cost of efficiency in terms of computation time
 23 or solution quality. This is why this controller is usually divided in two. First trajectories for the robot
 24 center of mass c^{ref} and the positions of contacts with the environment f^{ref} are found using a **Centroidal**
 25 **Dynamics Pattern Generator (CDPG)**. And, in turn a **WBC** computes an instantaneous controller that
 26 tracks these trajectories. More details about the **CDPG** can be found in the next paragraph. The whole
 27 body reference is in turn sent to the **Robot Hardware**, which can be either the simulation or the real robot.
 28 The feedback terms are based upon the measurements of the different sensors. The encoders evaluate
 29 the joint position (\tilde{q}). The inertial measurement unit (IMU) measures the angular velocity ($\tilde{\omega}_{IMU}$) and
 30 the linear acceleration (\tilde{a}_{IMU}) of the robot torso, which give us information about the orientation of the
 31 robot with respect to the gravity field. Finally the interaction with the environment is provided by the
 32 force sensors classically located at the end-effectors ($F_{EE} \in \{F_{RF}, F_{LF}, F_{RH}, F_{LH}\}$ where the subscripts
 33 have the following meaning EE : end-effector, RF : right foot, LF : left foot, RH : right hand, LH : left
 34 hand). All these information are treated in an **Estimator** to extract the needed values for the different
 35 algorithm. Finally the **Localization** block is dedicated to locate as precisely as possible the robot in its
 36 3D environment, Various implementations of this architecture have been proposed with various levels of
 37 success from the highly impressive Boston Dynamics System, to robots widely available such as Nao.

38 An open question is the robustness and the repeatability of such control system as well as its performance.
 39 In this paper we propose a benchmarking of the HRP-2 robot in various set-ups and provide performance
 40 indicators in scenarios which are possibly interesting for industrial scenarios.

41 The paper is structured as follows, first the paragraph 2 presents the related work on control and
 42 benchmarking for humanoid robots, then paragraph 3 depicts our precedent contribution in the Koroibot
 43 project and how it relates to this work, to continue, paragraph 4 lists the materials and different methods
 44 used to perform the benchmarking, in turn the paragraph 5 shows the experimental results using the
 45 indicators from paragraph 4, and finally the conclusion 6 summaries the contributions and results from this
 46 paper.

2 RELATED WORK

47 In this paragraph we present the work that has been done relative to the control and the benchmarking of
 48 humanoid robots.

2.0.1 Motion generation for humanoid robots

50 The different benchmarks included in this paper relate to **MPWBC** sketched in Fig. 1, so this section
 51 is dedicated to its related work. Several techniques are used to mathematically formulate this problem.

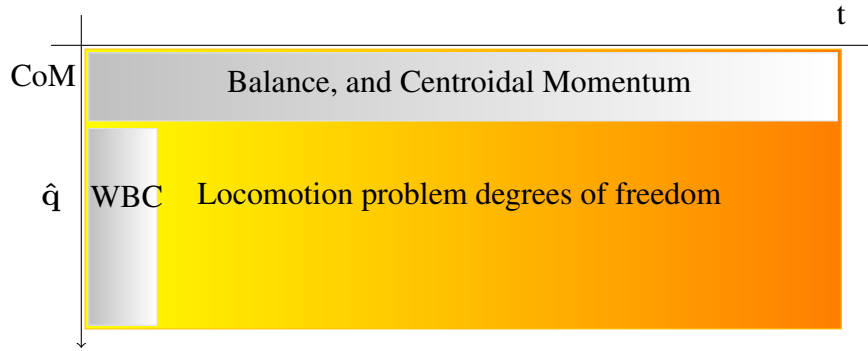


Figure 2. Representation of the size of the locomotion problem. The abscissa represent the duration of the predicted horizon and the ordinate the number of robot DoF.

52 For instance hybrid-dynamics formulations as proposed by Grizzle et al. (2010) or Westervelt et al.
 53 (2007) are efficient but difficult to generalize. The approaches used in this paper are based on mathematical
 54 optimization which is broadly used in the humanoid robotics community. More precisely, the problem of the
 55 locomotion can be described as an **Optimal Control Problem** (OCP). The robot generalized configuration
 56 (q^{ref}) and velocity (\dot{q}^{ref}) usually compose the state (\mathbf{x}). The future contact points can be precomputed
 57 by a **Motion Planner** or included in the state of the problem. The control of this system \mathbf{u} , can be the
 58 robot generalized acceleration (\ddot{q}^{ref}), the contact wrench (ϕ_k with $k \in \{0, \dots, \text{Number of Contact}\}$), or
 59 the motor torques (τ^{ref}). We denote by $\underline{\mathbf{x}}$ and $\underline{\mathbf{u}}$ the state and control trajectories. The following optimal
 60 control problem (OCP) represents a generic form of the locomotion problem:

$$\min_{\underline{\mathbf{x}}, \underline{\mathbf{u}}} \sum_{s=1}^S \int_{t_s}^{t_s + \Delta t_s} \ell_s(\mathbf{x}, \mathbf{u}) dt \quad (1a)$$

$$s.t. \quad \forall t \quad \dot{\mathbf{x}} = dyn(\mathbf{x}, \mathbf{u}) \quad (1b)$$

$$\forall t \quad \phi \in \mathcal{K} \quad (1c)$$

$$\forall t \quad \mathbf{x} \in \mathcal{B}_x \quad (1d)$$

$$\forall t \quad \mathbf{u} \in \mathcal{B}_u \quad (1e)$$

$$\mathbf{x}(0) = \mathbf{x}_0 \quad (1f)$$

$$\mathbf{x}(T) \in \mathcal{X}_* \quad (1g)$$

61 where $t_{s+1} = t_s + \Delta t_s$ is the starting time of the phase s (with $t_0 = 0$ and $t_S = T$). Constraint (1b) makes
 62 sure that the motion is dynamically consistent. Constraint (1c) enforces balance with respect to the contact
 63 model. Constraints (1d) and (1e) impose bounds on the state and the control. Constraint (1f) imposes the
 64 trajectory to start from a given state (estimated by the sensor of the real robot). Constraint (1g) imposes
 65 the terminal state to be viable Wieber (2008). The cost (1a) is decoupled $\ell_s(\mathbf{x}, \mathbf{u}) = \ell_x(\mathbf{x}) + \ell_u(\mathbf{u})$ and its
 66 parameters may vary depending on the phase. ℓ_x is generally used to regularize and to smooth the state
 67 trajectory while ℓ_u tends to minimize the forces. The resulting control is stable as soon as ℓ_x comprehends
 68 the L_2 norm of the first order derivative of the robot center of mass (CoM), Wieber et al. (2015).

69 Problem (1) is difficult to solve in its generic form. And specifically (1b) is a challenging constraint.
 70 Most of the time the shape of the problem varies from one solver to another only by the formulation of
 71 this constraint. The difficulty is due to two main factors: 1) There is a large number of degrees of freedom

72 (DoF). In practice we need to compute 36 DoF for the robot on a preview window with 320 iterations (1.6s)
73 to take into account the system inertia. 2) The system dynamics is non linear. Fig. 2 depicts the structure of
74 problem. To be able to solve the whole problem, represented by the full rectangle in Fig. 2 researchers used
75 nonlinear optimization. In this paper we evaluated a resolution of the **MPWBC** based on the formulation
76 given by Eq. 1. In this approach described in Koch et al. (2014), the authors computed a dynamical step over
77 motion with the HRP-2 robot, but this process can take several hours of computation. So simplifications
78 are necessary, for example Tassa et al. (2014), Koenemann et al. (2015) uses simplifications on the contact
79 model. This method is very efficient but is not suitable for complex contacts during walking for example.
80 Seminal works (Orin et al. (2013),Kajita et al. (2003b)) show that (1b) can be divided in two parts, the
81 non-convex centroidal dynamics (horizontal gray rectangle in Fig. 2) (Orin et al. (2013)) with few DoF
82 and the convex joint dynamics (vertical gray rectangle in Fig. 2). Kuindersma et al. (2014) and Sherikov
83 (2016) chose to deal the two gray part of Fig. 2 at once. They optimize for the centroidal momentum on
84 a preview horizon and the next whole body control. Qiu et al. (2011), Rotella et al. (2015), Perrin et al.
85 (2015) decouple the two separated gray rectangles in Fig. 2. They solve first for the centroidal momentum
86 and then for the whole body control. In general the centroidal momentum is still difficult to handle due
87 to its non-convexity. Finally Kajita et al. (2003a), Herdt et al. (2010), Sherikov et al. (2014) linearize
88 the centroidal momentum which provides a convex formulation of the locomotion problem. In Deits and
89 Tedrake (2014), the problem was formulated has a mixed-integer program (i.e. having both continuous and
90 discrete variables) in case of flat contact. In Mordatch et al. (2012), the same problem was handled using a
91 dedicated solver relying on a continuation heuristic, and used to animate the motion of virtual avatars.

92 2.1 Benchmarking

93 Different methods exist to benchmark robot control architectures, in del Pobil et al. (2006) the authors
94 argue that robotic challenges are an efficient way to do so. For example, the results of the DARPA
95 Robotics Challenge published in the Journal of Field Robotics special issues Iagnemma and Overholt
96 (2015) and Spenko et al. (2017), show the different control architecture in a determined context. Each
97 behavior successfully accomplished grants point to the team and the best team won the challenge. This
98 benchmarking was however costly as the robots had no system to support them in case of fall. In addition,
99 as it is mostly application driven it is necessary in evaluating the system integration but not the independent
100 subparts.

101 For the specific case of motion generation, it has been recently proposed by Brandao et al. (2017) to
102 use a scenario called "Disaster Scenario Dataset". It allows benchmarking posture generation (solved by
103 the **WBC**) and trajectory generation (**MPWBC**) using optimization. A set of problems is proposed by
104 means of foot steps locations (F_{RF} , F_{LF}). From this it is possible to compare algorithms realizing the
105 two functionalities (**WBC** and **MPWBC**). The evaluation is realized in simulation using the Atlas robot
106 and the ODE dynamic simulator. This first step is necessary but one step further is to benchmark a real
107 humanoid platform. For this paper we used a more systematic decomposition of the humanoid bipedal
108 locomotion Torricelli et al. (2015). Further description can be found in paragraph 4.7. This paper focuses
109 on evaluating the **MPWBC** and **WBC** on the **Robot Hardware**. The **Estimator** used in this context is
110 important but it is reflected in the stabilization process. The **Motion Planning** is not evaluated here as the
111 planned motion is always the same or solved at the **MPWBC** level. The **Localization** is provided by a
112 motion capture system.

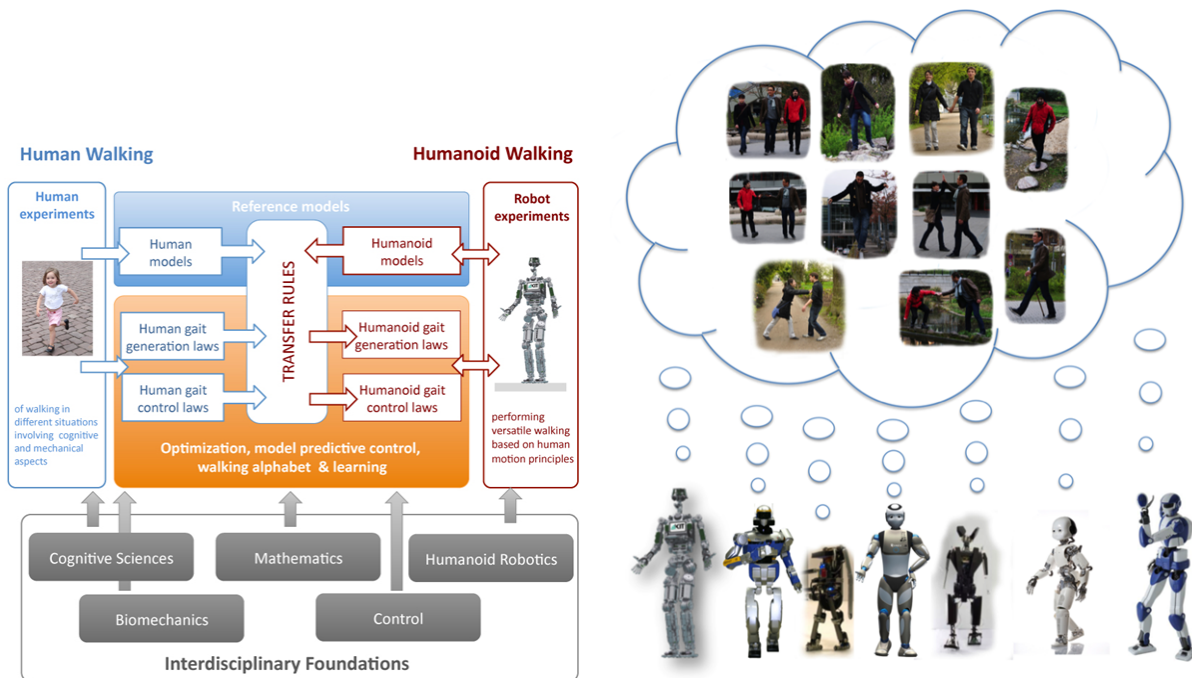


Figure 3. (left) Graphical representation of the scientific approach of the Koroibot project - (right) View of the humanoid robot used in the Koroibot project dreaming of human walking capabilities

3 THE KOROIBOT PROJECT AND OUR PRIOR CONTRIBUTIONS

113 The work presented in this paper takes its root in the context of the European project Koroibot (<http://www.koroibot.eu/>).

115 3.0.1 General purpose

116 The goal of the Koroibot project was to enhance the ability of humanoid robots to walk in a dynamic and
 117 versatile way, and to bring them closer to human capabilities. As depicted in Fig. 3-(left), the Koroibot
 118 project partners had to study human motions and use this knowledge to control humanoid robots via
 119 optimal control methods. Human motions were recorded with motion capture systems and stored in an open
 120 source data base which can be found at <https://koroibot-motion-database.humanoids.kit.edu/>.
 121 With these data several possibilities were exploited:

- 122 ■ Criteria that humans are assumed to minimize using Inverse optimal control.
- 123 ■ Transfer from human behaviors to robots was done with walking alphabets and learning methods
 124 Mandery et al. (2016).
- 125 ■ These human behavior was safely integrated in robots applying optimal controllers.
- 126 ■ Design principles were derived for new humanoid robots. Mukovskiy et al. (2017); Clever et al. (2017)

127 3.0.2 The robot challenges

128 In order to evaluate the progress of the algorithms at the beginning and at the end of the project, a set
 129 of challenges were designed focusing specifically on walking (see Fig. 4). Fig. 3-(right) shows all the
 130 robot hosted by the various partners. All the team owning a robot had to perform some of these challenges
 131 considering the current and potential state of their robots and controllers.

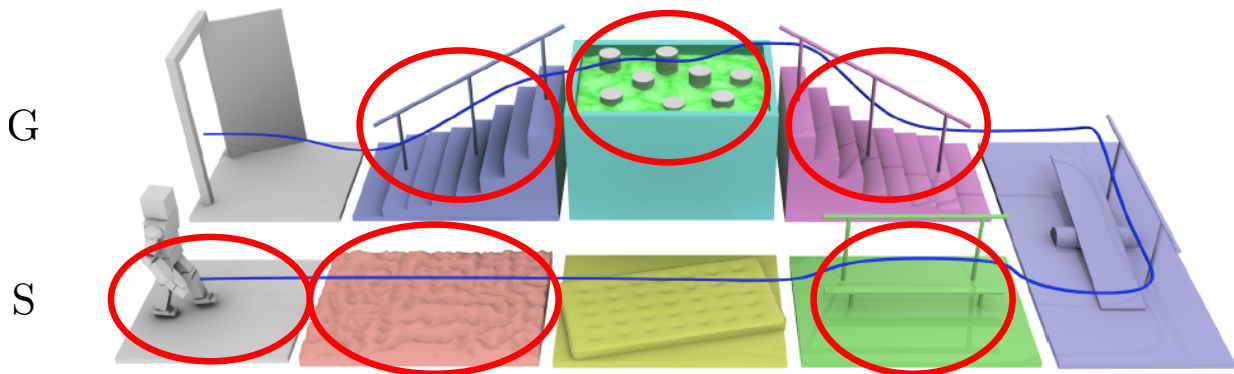


Figure 4. Challenges of the Koroibot project. In red the challenges chosen by the LAAS-CNRS.

132 3.0.3 The Key Performance Indicators (KPI)

133 In this context and in collaboration with the H2R project, a detailed set of key performance indicators
 134 (KPI) have been proposed Torricelli et al. (2015). These KPI try to capture all the bipedal locomotion
 135 patterns. Specific sub-functions of the global motor behaviors were analyzed (see Fig. 5-(right)). The results
 136 are expressed as two different sub-function sets. First, the sub-functions associated to body posture task
 137 with no locomotion. And second the same sub-functions but including the robot body transport. The initial
 138 condition may vary depending on the experiment to perform. This is the idea of the intertrial variability. The
 139 sub-functions are also classified by taking into account the changes in the environment or not. Each of these
 140 functions can be evaluated for different robots using the criteria depicted in Fig. 5-(left). The performance
 141 are classified in two sub categories, quantitative performance and human likeness. In addition there are
 142 indications on the last two columns if the criteria is applicable on a standing task or on a locomotion task.
 143 Again, all the team owning a robot had had to perform an evaluation of these KPI, considering the current
 144 and potential state of their robots and controllers.

145 3.1 The work done in the Koroibot context

146 In the Koroibot context the gepetto team evaluated the KPI one the robot HRP-2 (second robot from the
 147 left in (Fig. 3-(right))). Among the challenges presented in Fig. 4, we considered the following ones:

- 148 ■ walking on a flat ground,
- 149 ■ walking on an uneven ground,
- 150 ■ walking on a mattress,
- 151 ■ walking on a beam without handrail,
- 152 ■ climbing a stair case with/without handrail,
- 153 ■ walking on stepping stones,
- 154 ■ going down a stair case without handrail,

155 They are depicted by red circles in Fig. 4. In addition to these challenges we added the perturbation
 156 rejection. Considering the selected challenges we picked the following KPI sub-function:

		Abilities		Benchmarks			
		Name	Description	Benchmark	Applicability Posture	Transport	
Performance	Stability	Intratrial Stability	Ability to Maintain Equilibrium Within a Single Trial	Time Until Falling Cycles Until Falling	X	X	
		Intertrial Stability	Ability to Maintain the Equilibrium Across Different Trials	Success Rate Across <i>N</i> Different Trials	X	X	
		Gross Body Equilibrium	Ability to Maintain Equilibrium Over the Base of Support	Energy Stability Margin (ESM) Maximum Accepted Disturbance Amplitude Maximum Accepted Disturbance Frequency	X	X	
	Efficiency	Global Energy Consumption	Ability to Transport Body with Low Energetic Costs	Specific Energetic cost of Transport C_{st} Specific Mechanical Cost of Transport C_{mst}		X	
		Passivity	Ability to Minimize Joint Torques During Walking	Passive Gait Measure (PGM)		X	
		Reaction Time	Ability to Promptly React to Disturbance or External Command	Time from Input and Initiation of Motor Action	X	X	
	Human Likeness	Kinematics	Gross Body Motion	Motion of the Whole Body Expressed by Global Variables	CoM Trajectory (Correlation, Dynamic Time Warping) Gait Harmony Body Sway (Frequency Response Function) Natural Looking Motion	X	X
			Individual Joint Motion	Motion of the Single Joints or Limbs Taken Separately	Joint Trajectory (Correlation, Dynamic Time Warping) Knee, Ankle Forefoot Rocker	X	X
			Interlimb Coordination	Ability to Coordinate Between Different Body Parts	Symmetry (Ratio Index) Trunk/Arm Motion	X	X
		Dynamics	Intralimb Coordination	Ability to Move Multiple Joints of the Same Limb Coordinately	Kinematic Synergies	X	X
Gross Body Kinetics			Forces Exerted Between the Whole Body and the Environment	Ground Reaction Forces (Correlation, Dynamic Time Warping)	X	X	
Single-Joint Kinetics			Force Exerted Among Limbs	Joint Torques (Correlation, Dynamic Time Warping) Froude Number (Dimensionless Gait Velocity)	X	X	
Human Likeness		Dynamics	Dynamic Similarity	Ability of Having Leg Pattern Dynamically Similar to Most Legged Animals	Dynamic Gait Measure (DGM)		X
			Dynamics	Ability to Use Falling State for Body Progression	Impulse Response Function (IRF)	X	X
		External Compliance	Ability to Respond Resiliently to External Disturbances	Active/Net Joint Torque	X	X	
		Internal Compliance	Ability to Store and Release Energy		X	X	

		Function			
		Body Posture	Body Transport		
Environment	Stationary	No	Static Horizontal Surface	Horizontal Ground at Constant Speed	
			Static Inclined Surface	Sloped Ground Stairs	
		Yes	Different Static Surfaces	Variable Slopes	Irregular Terrain
				Slippery Surface	
	In Motion	No	Continuous Surface Tilts	Treadmill at Constant Speed	
			Continuous Surface Translations	Soft Terrain with Constant Compliance	
		Yes	Bearing Constant Weight	Bearing Constant Weight	Bearing Constant Weight
				Pushes	Pushes
				Sudden or Pseudorandom Surface Tilts	Treadmill at Variable Speed (Including Start-Stop)
Sudden Surface Translations	Seesaw				
Body Sway Referenced Platform (BSRP)	Soft Ground with Variable Compliance				

Figure 5. (left) Performances indicators (right) The motor skills considered in the benchmarking scheme. This scheme is limited to bipedal locomotion skills. The concept of intertrial variability represent modifications of the environment between trials. (dashed) Motor skills evaluated in Naveau (2016) (not dashed) Motor skills evaluates in this paper.

- 157 ■ horizontal ground at constant speed,
- 158 ■ stairs,
- 159 ■ bearing constant weight (the robot’s own weight)
- 160 ■ success rate across *N* different trials,
- 161 ■ mechanical energy,
- 162 ■ mechanical plus electrical energy,

163 All these choices are shown in Fig. 5 by red ellipses on the table. The mathematical details and results
 164 are presented below in paragraph 4.7.

4 MATERIALS AND METHODS

165 In this paragraph the experimental setups used to compute each of the performance indicators given in 4.7
 166 are described. It also presents the motor skills given in Fig. 5 and their implementation. In addition to this,
 167 the algorithms used to perform the different test are depicted in paragraph 4.8.

4.1 Different temperatures

169 LNE is equipped with temperature varying rooms which allowed us to quantify some of the performance
 170 indicators between 5°C and 45°C. In this way, we evaluated the robustness and limits of our robot for all

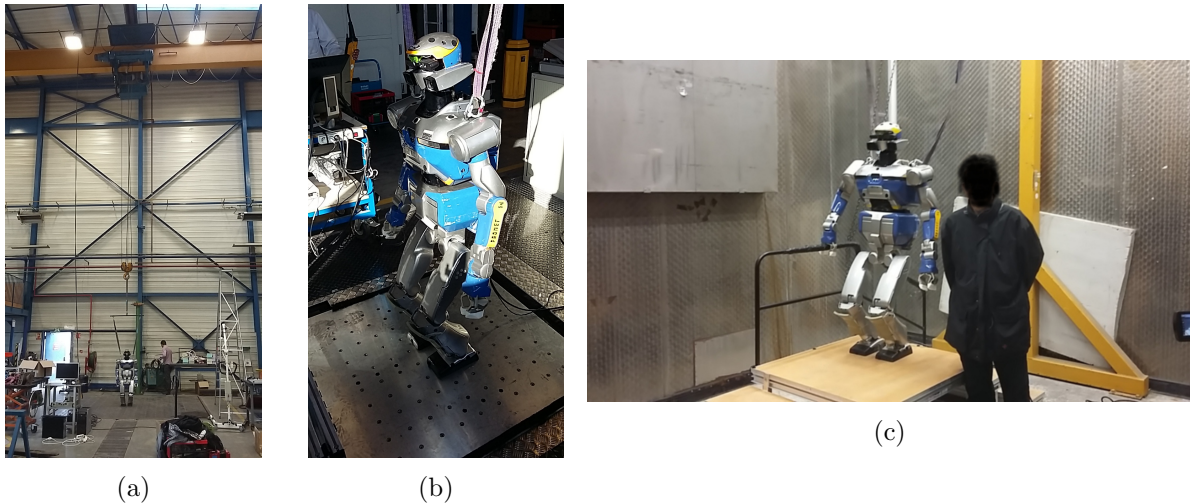


Figure 6. Pictures of the experimental setup at LNE (a) the robot hang up to walk on a slope (b) the translational plate (c) the temperature controlled chamber (end of the robot climbing 15 cm at 10°C)

171 the performance indicators. It appeared that the robot behavior deteriorates at low temperatures. At 5°C it
 172 was not possible to perform the calibration procedure as the robot could not move. At 10°C the friction
 173 are sufficiently low such that the robot could move. Another phenomena occurs above 40°C: thermal
 174 protection prevents the robot from moving if the temperature is too high. This happens at 40°C after few
 175 motions due to internal temperature build up. In this room, apart from these extreme cases, the motions and
 176 indicators measurements have be performed as expected on a flat ground or on the stairs from the Koroibot
 177 project. This staircase is made of 4 stairs and a platform with each stair separated by 15 cm height. The
 178 dimension of one stair case is 1 m × 0.25 m × 0.05 cm.

179 4.2 Tilted surfaces

180 In the context of the body skills in motion, we considered tilting surfaces. This was tested with the
 181 stabilizer commercially available with HRP-2. The setup is a platform which can be tilted upward and
 182 downward on one side with an hydraulic actuator. The surface was tilted continuously until the robot fell
 183 off. On the other hand, we tested walking algorithms with different angles (pointing up or down) until the
 184 robot fell down. Tests were realized with the robot pointing down, pointing up and across the slope. In
 185 Fig. 5 this corresponds to Body Posture - Continuous Surface Tilts.

186 4.3 Horizontal translations

187 We used a mobile plate controlled in the horizontal plane to perform continuous oscillating surface
 188 translations at various frequencies and various amplitudes. The platform was using a hydraulic actuator.
 189 The aim was to find the frequency and the amplitude that the controlled robot is able to sustain. In Fig. 5
 190 this corresponds to Body Posture - Continuous Surface translations.

191 4.4 Bearing

192 In order to test bearing weights with the robot, we added bags of 5 kgs to 15 kgs in such way that the
 193 robot balance is maintained. This approach is a bit limited as they are several ways to bear a weight. Indeed
 194 it can be done with a backpack, in collaboration with someone, by holding the object against its chest. Each

195 of this approach comes with its own specific constraint. In order to avoid such constraints, we decided to
196 take the most simplest choice and hang soft weights on the front and the back of the chest. In Fig. 5 this
197 corresponds to Body Transport - Bearing Constant Weight.

198 4.5 Pushes

199 This paragraph presents the pushes experiments. We tried to find the sufficient force to make the robot
200 fall down. This was achieved by using a stick on top of which was fixed a force sensor displaying the
201 maximum force measured during a physical interaction. The experience was realized while the robot was
202 standing and walking. The force was applied in the sagittal and frontal planes until making HRP-2 fall. The
203 force was applied behind the waist of the robot. This part of HRP-2 was made specifically soft to support
204 impacts. The walking part is the most difficult in terms of repeatability as the robot might be in different
205 foot support and therefore be less stable depending on the situation. In Fig. 5 this corresponds to Body
206 Posture - Pushes and Body Transport - Pushes.

207 4.6 Data

208 A CAD model of this staircase used is available on the github repository where all the log
209 of the experiments are also present: https://github.com/laas/koroibot_KPI. All the computation
210 performed on the logs and implementing the key performance indicators are available here:
211 <https://github.com/laas/EnergyComputation>.

212 4.7 Key Performance indicators (KPI)

213 In this section the performance indicators used to evaluate the humanoid robot HRP-2 are described.
They are mostly based on the work proposed in Torricelli et al. (2015). In the Koroibot project we used key

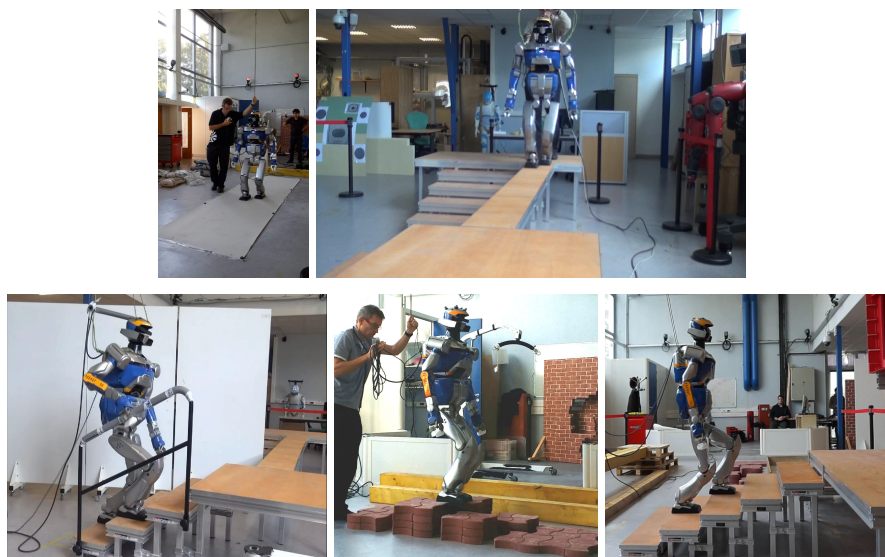


Figure 7. Sample of the experimental setup of the Koroibot project in LAAS-CNRS

214 performance indicators (KPI) to analyze the behavior of the robot at the beginning and at the end of the
215 project. These results lead us toward the improvements to be made. In 2013 the algorithm mostly used and
216 implemented on HRP-2 in LAAS-CNRS where the walking pattern generators described in Morisawa et al.
217 (2007) and in Herdt et al. (2010). The performance indicators chosen were:

- 219 ■ The execution time $T_M = t_{end} - t_{begin}$, where t_{begin} is found when the sum of the norm of the motor
 220 axis velocities reaches 6 rad s^{-1} for the first time in the log and t_{end} is when the sum of the norm of
 221 the motor axis velocities is below 0.5 rad s^{-1} .
 222 ■ The walked distance, being the distance between the final base position and the first one. The base
 223 pose is reconstructed using an odometry with the joint positions only. The drift of this odometry is
 224 8 cm over a 3.6 m during a straight walk.
 225 ■ The success rate, being the number of time a specific task could be performed without fall, over the
 226 total number of trial of the task.
 ■ The maximum tracking error from the planned trajectory,

$$TrackingError(t) = \int_t^{t+0.1} |q^{ref} - \tilde{q}| dt / 0.1$$

$$MaxTrackingError = \max_t (TrackingError(t))$$

227 with $TrackingError$ being the average normed difference between the desired joint trajectory
 228 (q^{ref}) and the joint pose measured from the encoder (\tilde{q}) during 0.1 s starting at time t . And
 229 $MaxTrackingError$ being the maximum value of the $TrackingError$ function.

- The mechanical energy consumed normalized over the walking distance D and the execution time T_M .

$$E_{mechanical} = \int_{t_{begin}}^{t_{end}} |\tau \omega| dt / (T_M D)$$

230 with $E_{mechanical}$ being the integral over time of the mechanical power, τ being the torques applied at
 231 the robot joints and ω being the velocity of the robot joints

- The electrical energy dissipated by the motor resistance normalized over the walking distance D and the execution time T_M ,

$$E_{motor\ resistance} = \int_{t_{begin}}^{t_{end}} R i^2 dt / (T_M D) = \int_{t_{begin}}^{t_{end}} R k_c^2 \tau^2 dt / (T_M D)$$

232 with $E_{motor\ resistance}$ being the integral over time of the electric power dissipated, R being the motor
 233 resistances, k_c being the electric motor torque constant and τ being again the torques applied at the
 234 robot joints.

- The total energy consumed during the walking distance D and the execution time T_M ,

$$E_{total} = E_{mechanical} + E_{motor\ resistance} + E_{electronics}$$

with E_{total} being the sum of the energy consumed by the system normalized over the walking distance D and the execution time T_M , and $E_{electronics}$ being the energy consumed by the on-board electronic cards. $E_{electronics}$ is neglected in this study so:

$$E_{total} = E_{mechanical} + E_{motor\ resistance}$$

- The mechanical cost of transport and the total cost of transport,

$$E_{\text{mechanical cost transport}} = \int_{t_{\text{begin}}}^{t_{\text{end}}} |\tau\omega| dt / (m g D)$$

$$E_{\text{total cost transport}} = \left(\int_{t_{\text{begin}}}^{t_{\text{end}}} |\tau\omega| dt + \int_{t_{\text{begin}}}^{t_{\text{end}}} R k_c^2 \tau^2 dt \right) / (m g D)$$

235 with $E_{\text{mechanical cost transport}}$ and $E_{\text{total cost transport}}$ being the respectively the mechanical and total
 236 cost of transport, m being the total mass of the robot, and $g = 9.81 \text{ m s}^{-2}$ the gravity constant.

- The Froude number,

$$F_r = \frac{v}{\sqrt{gl}}$$

$$v = \frac{D}{T_M}$$

237 where v is the robot center of mass mean velocity along the horizontal plane,, and l is the leg length.
 238 This number represents the ratio between the kinetic energy and the potential energy. It can also be
 239 interpreted as an indicator on the stepping frequency.

240 The trajectories were generated off line and repeatedly played on the robot to analyze their robustness.
 241 Views of the experimental setups can be seen in Fig. 7.

242 4.8 Motion generation for humanoid robots locomotion

243 This section explains the links between the motion generation architecture depicted in Fig.1 and the
 244 Key Performance Indicators given in the paragraph 4.7. The set of function entitled body posture depicted
 245 in Fig.1-(right) represents the behavior which is provided by what is called a whole-body controller. It
 246 consists in two parts:

- 247 • an estimator, which provides the orientation of the robot with respect to the gravity field and the
 248 positions of the end-effectors in contact with the environment.
- 249 • a whole-body controller which guarantee that the robot balance is maintained with respect to c^{ref} ,
 250 f^{ref} and possibly a q^{ref} .

251 In this paper we have evaluated independently only one whole body motion controller. It is the stabilizer
 252 provided by Kawada Inc. We give detailed performances evaluation of this controller in the experimental
 253 part of this paper. It was described in various paper such as Kajita et al. (2007) and Kajita et al. (2001).

254 The set of function entitled body transport depicted in Fig.1-(right) in this paper are four **CDPG** and
 255 one **MPWBC**. The four **CDPG** evaluated in this paper are the following ones: Carpentier et al. (2016),
 256 a multi-contact centroidal dynamic pattern generator used to climb stairs with given contact positions,
 257 Kajita et al. (2003a) the original walking pattern generator implemented by Shuuji Kajita with given
 258 foot steps, Morisawa et al. (2007) an analytical walking pattern generator allowing immediate foot step
 259 modifications, Naveau et al. (2017) a real time non linear pattern generator able to decide autonomously
 260 foot-steps positions. In each case the goal of the **CDPG** is to generate a center of mass trajectory and
 261 the foot-steps trajectories. For Kajita et al. (2003a), Naveau et al. (2017), and Morisawa et al. (2007) a
 262 dynamical filter is used to correct the center of mass trajectory to improve the dynamical consistency of

263 the motion. In each case, a whole body motion generator (not to be confused with a whole body motion
 264 controller) is used without feedback to generate the reference position q^{ref} , and the desired z^{ref} which is
 265 then send to the stabilizer. For Naveau et al. (2017) and Morisawa et al. (2007) we used the stack of task
 266 described in Mansard et al. (2009) as a Generalized Inverse Kinematics scheme. In Carpentier et al. (2016)
 267 a Generalized Inverse Dynamics was used to generate the reference value for q^{ref} and c^{ref} . The **MPWBC**
 268 provides directly the controls. The one used is from Koch et al. (2014) using the Muscod-II Diehl et al.
 269 (2001) nonlinear solver.

5 EXPERIMENTS

270 In this paragraph we present the numerical results obtained from the computation of the KPI explained in
 271 details in paragraph 4.7 for each set of experiments. As a reminder here the list of the KPI:

- 272 ■ walked distance,
- 273 ■ success rate,
- 274 ■ max tracking error,
- 275 ■ duration of the experiment,
- 276 ■ mechanical joint energy,
- 277 ■ actuators energy,
- 278 ■ cost of transport,
- 279 ■ mechanical cost of transport,
- 280 ■ Froude number.

281 A video displaying a mosaic of all the experiments is available at the following URL:
 282 <https://www.youtube.com/watch?v=djWGs44JmY&feature=youtu.be>.

283 5.1 Climbing stairs

284 5.1.1 Stairs of 10 *cm*

285 In this experiment, the humanoid robot HRP-2 is climbing stairs of 10 *cm* height without any handrail.
 286 The difficulty of this task is that the robot has to do quite large steps and to perform vertical motion.
 287 Because of the large motion issue the robot is climbing one stair at a time. Which means that the robot put
 288 one foot on the next stair and the other on the same stair. This avoid a too large joint velocity that the robot
 289 could not track.

290 Morisawa et al. (2007) **CDPG** was evaluated at the beginning of the project although the variation of
 291 height violates the assumption of the cart table model. But thanks to the dynamical filter the motion
 292 generated was sufficiently dynamically consistent so that the stabilizer could cope with the situation. The
 293 test was performed in a room at $20^{\circ}C$. The KPI results can be seen in Fig. 11-(tool upstairs).

294 The other test was performed at the end of the project on the **CDPG** Carpentier et al. (2016). This time
 295 the **CDPG** took into account the center of mass height variation but not the whole body motion. The
 296 stabilizer should theoretically less trouble to compensate for the simplifications made. For Carpentier et al.
 297 (2016) three different temperatures were tested: $10^{\circ}C$, $20^{\circ}C$ and $35^{\circ}C$. The numerical results are depicted
 298 in Fig. 8.

299 Interestingly, the temperature level has a direct impact in terms of mechanical cost as it diminishes with
 300 the increase in temperature. It is reflected in the tracking error. This intertrial variation do not come from

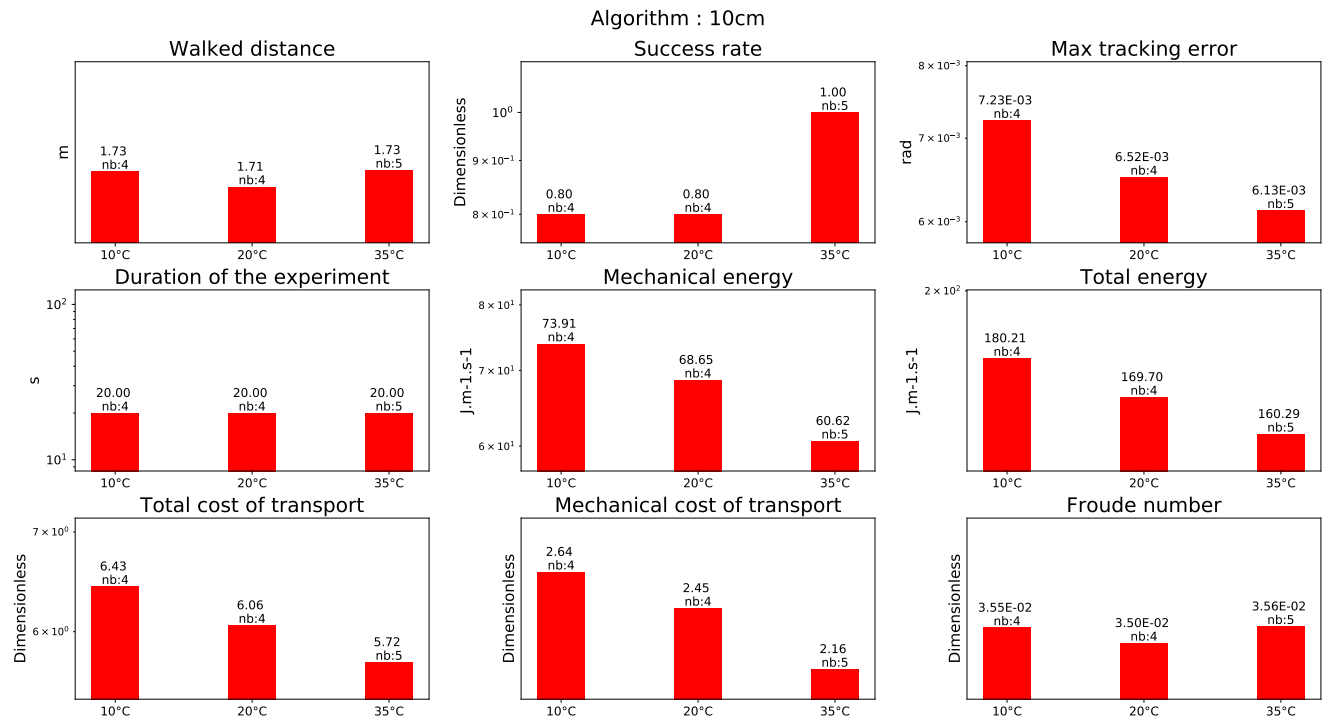


Figure 8. Climbing 10 *cm* stairs without handrail

301 the change of reference trajectory as it is strictly the same for every trial. There is a level of adaptation due
 302 to the stabilizer, but each temperature has been tested at least 4 times. A possible explanation is the fact
 303 that the grease in the harmonic drive generate less friction with higher temperature.

304 As the cost of transport is dimensionless it allows to compare the two motions regardless of their duration.
 305 It is then interesting to see that the cost of transport in Fig. 11-(tool upstairs) and in Fig. 8-(10°C) are
 306 very similar. And that at the same temperature the total cost of transport for Carpentier et al. (2016)
 307 **CDPG** is 9.6% better (from 6.71 to 6.06). One explanation is that the motion from Carpentier et al. (2016)
 308 **CDPG** being more dynamically consistent, the stabilizer consume less energy to compensate for the model
 309 simplifications.

310 5.1.2 Stairs of 15 *cm*

311 In this experiment, the humanoid robot HRP-2 is climbing stairs of 15 *cm* height using a handrail. In
 312 addition the robot is not using any stabilization algorithm, because there are non-coplanar contacts.

313 In this setup the Morisawa et al. (2007) **CDPG** has to be used without handrail because of the model
 314 simplifications. Trials has therefore been done using a **WBC** (described in Mansard et al. (2009)) without
 315 the handrail. The results show that the current demanded by the motors went up to 45 *A*. And because the
 316 HRP-2 batteries can not provide more than 32 *A*, all trial failed. This is the reason why the results are not
 317 shown in this study.

318 Nevertheless, tests using the handrail could be performed with Carpentier et al. (2016) **CDPG**. The
 319 corresponding results are depicted in Fig. 9. It confirms that the energy is decreasing with the increase of
 320 temperature without the stabilizer. Note that the energy spend by the robot is clearly higher than for the
 321 experience on the 10 *cm* stairs, i.e. a 36% of increase for the energy of walking.

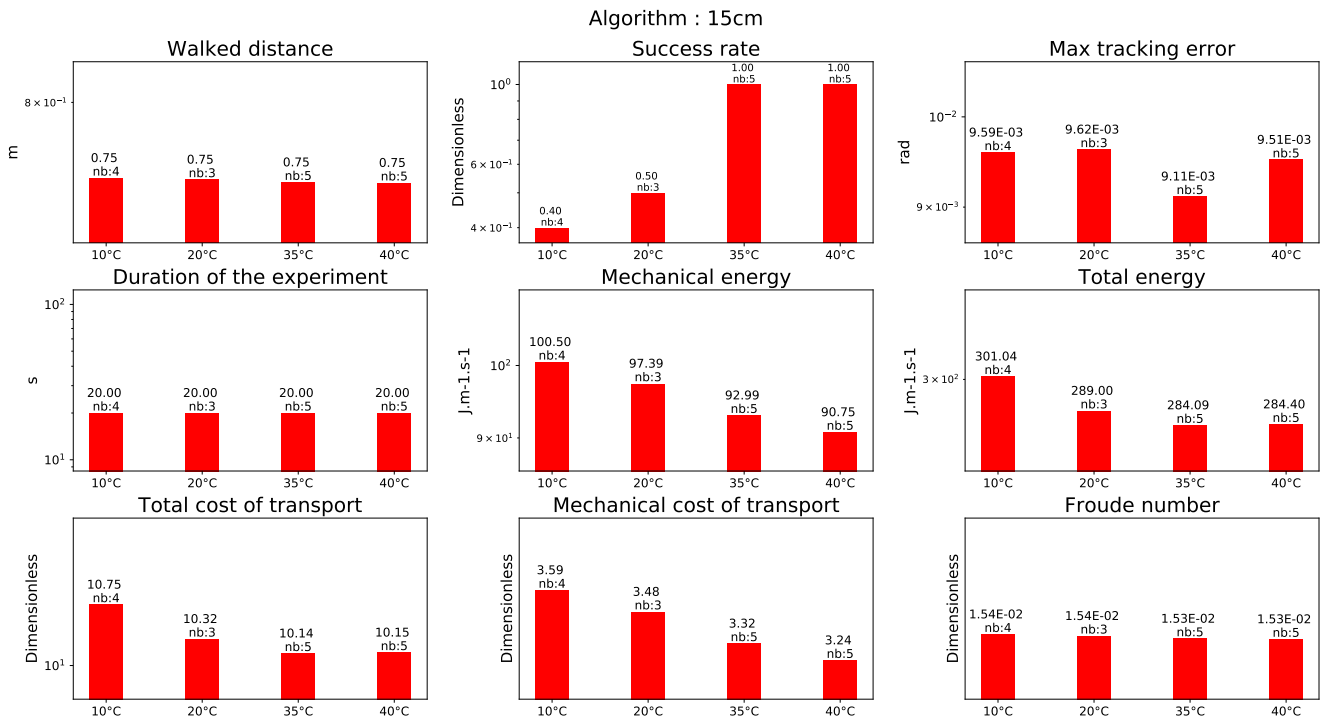


Figure 9. Climbing 15 cm stairs with a handrail

322 5.1.3 Stepping Stones

323 In this experience, the humanoid robot HRP-2 had to go up and down on stairs made of red interlocking
 324 paving stones. Between each stairs there is a height difference of ± 5 cm. It is using the **CDPG** described
 325 in Morisawa et al. (2007). It is slightly different from the previous experiments because there are holes
 326 between the stairs. To cope with this, the generated trajectories had to always change the height of the next
 327 support foot. As the paving stones were always slightly moving due to the robot weight the balance was
 328 difficult to obtain in a reliable way. As indicated in the graph depicted in Fig.11, despite a success rate
 329 of 1, the tracking error reaches a level ($8e^{-03}$). This tracking error is greater than the one obtained by the
 330 10 cm climbing experiment at $10^{\circ}C$ but lower than the one obtained by the 15 cm climbing experiment
 331 at $35^{\circ}C$ (which is the lower for this temperature and the **CDPG**). A possible explanation why the energy
 332 consumption is greater is greater than the 10 cm climbing stairs is mostly due to the unstability of the
 333 stones and the fact that in this experiment the robot climb the stairs in a human fashion, i.e not one stair at
 334 a time.

335 5.2 Walking on a beam

336 This experiments was realized using the **CDPG** Morisawa et al. (2007). In this experiment the humanoid
 337 robot HRP-2 is walking on a beam. Initially, the experiment success rate on a real beam was around 20 %.
 338 This rate was improved to achieve a 90 % success rate, thanks a new implementation of the dynamical
 339 filter presented in Kajita et al. (2003a). It reduced the drift which is important as the beam length is 3 m
 340 long. This could be probably improved by a proper vision feed-back. In this study though the robot walked
 341 on a normal ground as if it where on a beam. The reason is the absence of a beam in the temperature
 342 controlled room. This means that the balance problem is exactly the same though the precision of the foot

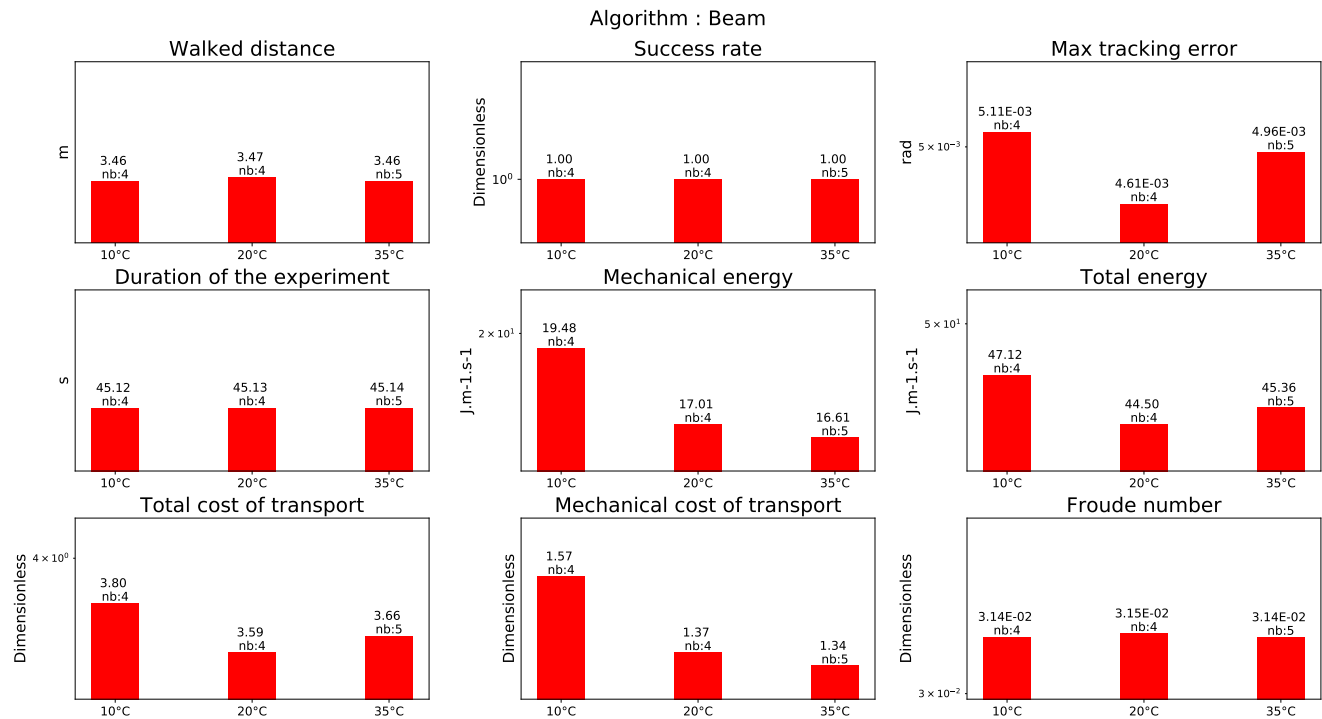


Figure 10. Walking on a beam

343 step location is discarded. Hence in this study the success rate is 1. The corresponding result is depicted in
 344 Fig. 10.

345 To perform the motion, the robot has to execute faster motions with its legs than compare to straight
 346 walking. It is emphasized by the increase of the cost of transport compared to normal straight walking (see
 347 Fig.13). Though the robot's leg are moving faster, the step frequency is lowered compared to a normal
 348 walking in order to keep the joint velocities in the feasible boundaries. This is reflected by the fact that the
 349 Froude number is around 35% less that a straight walking one (see Fig.13).

350 5.3 Straight flat ground walking

351 5.3.1 Temperatures

352 In the temperature controlled room the humanoid robot HRP-2 is performing a 2 m straight walking
 353 following the implementation of Kajita et al. (2003a). The corresponding result is depicted in Fig. 13. Note
 354 that the energy with respect to the temperature is following the same trend as for the experiments on the
 355 stairs and on the beam.

356 We also tested the algorithm Naveau et al. (2017) at 10°C. The total cost of transport is higher than the
 357 algorithm Kajita et al. (2003a) at the same temperature but lower than the one used for going over the beam.
 358 It is however largely less than the total cost of transport for climbing stairs at 10°C.

359 The fact that the energy cost is higher for Naveau et al. (2017) than for Kajita et al. (2003a) at the same
 360 temperature is that Naveau et al. (2017) provide a higher range of motion but the generated motion are
 361 closer to the limit of the system, so the stabilizer spend more energy to compensate for this.

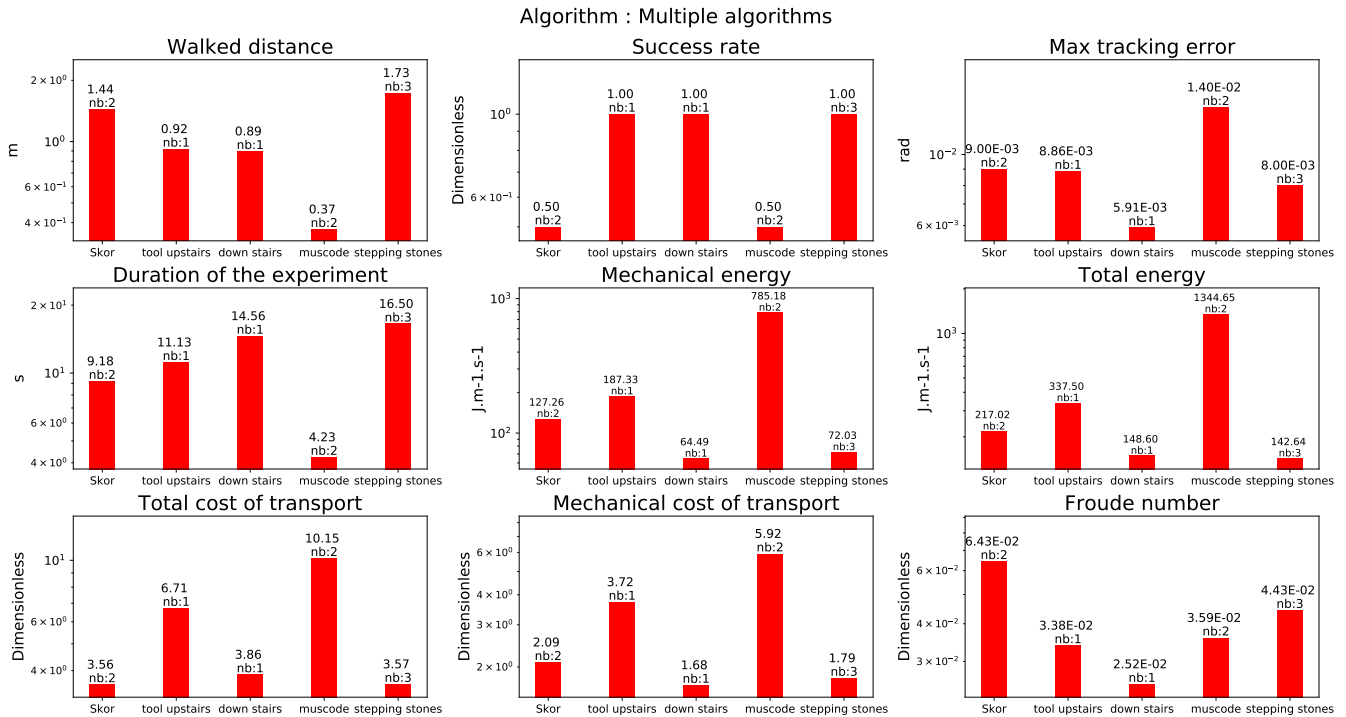


Figure 11. Multiple algorithms: going up with a tool on a wooden pallet 10 cm (tool upstairs), going down on a wooden pallet 10 cm (down stairs), going over an obstacle solving an **OCP** approach (muscode), stepping on a interlocking paving stones (stepping stones)

362 5.3.2 Bearing weights

363 We made the humanoid robot HRP-2 walks while bearing weights at ambient temperature between 15°
 364 and 19°. The two algorithms Kajita et al. (2003a) and Naveau et al. (2017) were tested. The robot was able
 365 to walk while carrying up to 14 kg for the two algorithms. Note that, as expected, the effort to compensate
 366 for the additional weight reflects in the cost of transport.

367 5.3.3 Pushes

368 We performed pushes in the lateral direction and in the frontal direction while the robot was walking
 369 along a straight line. The two algorithms Kajita et al. (2003a) and Naveau et al. (2017) were again tested.
 370 In our case, the tested algorithm was not able to modify its foot-steps according to the pushes in contrary to
 371 the impressive work of Takumi et al. (2017). For this specific set of experiments with push from the back,
 372 the robot was able to sustain forces from 31 N to 47 N. Pushes applied in the lateral plane were varying
 373 from 23 N to 40 N. For Kajita et al. (2003a), the cost of transport has a value of 3.31 similar to the beam
 374 behavior. It is lower than the cost of transport for climbing stairs. The cost of transport for Naveau et al.
 375 (2017) is of 4.08. For both algorithms pushes are among the most consuming behaviors. It is due to the
 376 stabilizer compensating for the perturbation.

377 5.3.4 Slopes

378 The robot walked on a straight line while being on a slope of various angles ([1° – 3.0°]) -and with two
 379 possible directions (upward or downward). The two algorithms Kajita et al. (2003a) and Morisawa et al.
 380 (2007) were tested. For Kajita et al. (2003a) the cost of transport is higher than standard straight walking

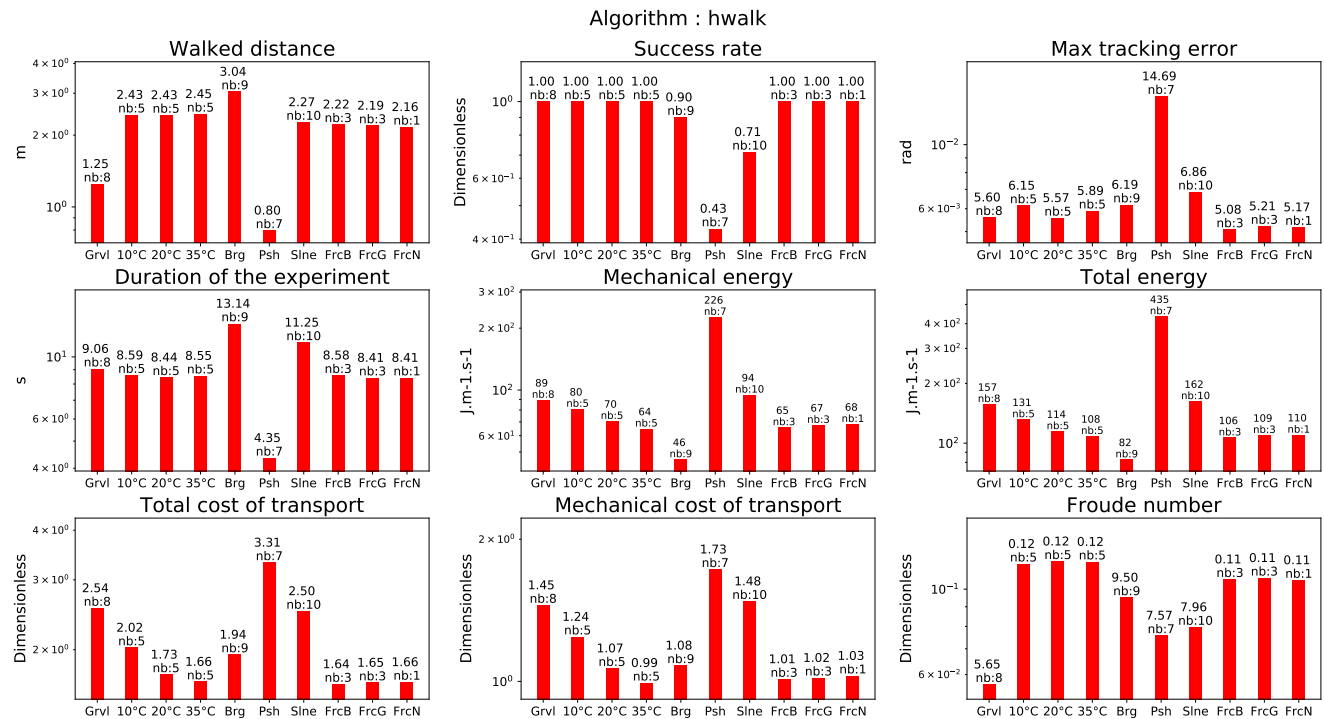


Figure 12. Straight walk with Kajita’s walking pattern generator Kajita et al. (2003a)

381 but far less than during the pushes. For Morisawa et al. (2007) the cost of transport is higher than even
 382 the pushes for Kajita et al. (2003a) and the same level than the beam. It can be explained by the fact that
 383 when the experiment has been realized the dynamical filter was not used. Therefore the stabilizer had to
 384 compensate for the discrepancy between the motion dynamic and the reference of the center of pressure.
 385 An algorithm able to estimate the ground slope and adapt to it would probably increase the efficiency of
 386 this motion.

387 5.3.5 Frictions

388 The robot walked on carpets with different textures implying different friction coefficients bought in
 389 a home center. In this case, we did not see any consequences with the **CDPG** Kajita et al. (2003a). This
 390 is probably due to the particular shape of the soils which is one way to affect the friction coefficient. A
 391 possible extension of this work would be to use more slippery ground. But a proper way to handle such
 392 case is to implement a slip observer such as it was done Kaneko et al. (2005).

393 5.3.6 Uneven terrain

394 The robot walked over gravels of calibrated size bought in a nearby home center. We tested several
 395 diameters with the **CDPG** Kajita et al. (2003a). The robot was able to walk on gravels of size up to 8 mm.
 396 Beyond this size, the robot was falling. Note that in Fig.13 the cost of transport is slightly more expensive
 397 than classical straight walking in nominal temperature, but not much than walking at 10°C. It is far less
 398 expensive than climbing a slope or to counteract pushes. As expected it has no impact on the frequency of
 399 the footstep as can be seen in the Froude Number.

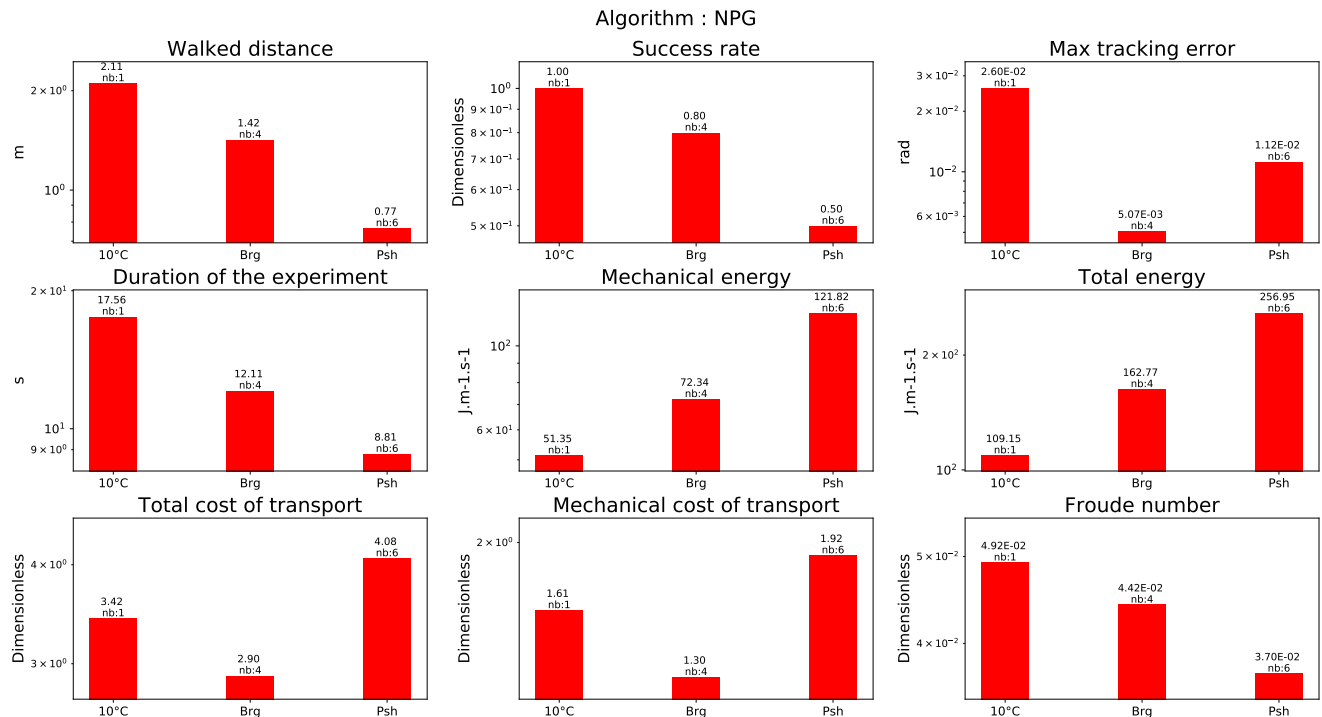


Figure 13. Straight walk with the walking pattern generator described in Naveau et al. (2017)

400 5.3.7 Walking over an obstacle

401 We have computed the same performance indicators for the behavior described in Koch et al. (2014) in
 402 the frame of the Koroibot project. This work is quite different from the others as it implements a **MPWBC**
 403 under the formulation of an Optimal Control Problem given by Eq.1. The solution of this problem was
 404 computed by the Muscod-II Diehl et al. (2001) solver. As the solver is trying to maximize a solution which
 405 is not on a reduced space (the centroidal dynamics for the previous algorithms) but on the whole robot,
 406 the solution find is near real constraints of the robot in terms of joint position, velocity, acceleration and
 407 torques. This is reflected in the cost of transport which is very high, 10.15, almost as high as the climbing
 408 stair of 15cm (see Fig.11-(muscode)).

409 5.4 Stabilizer

410 The stabilizer described in Kajita et al. (2007) and Kajita et al. (2001) was extremely resilient during all
 411 the tests. An horizontal plane generated oscillations along the sagittal plane and the perpendicular plane
 412 at 1 Hz and 2 Hz at various amplitude [10, 20, 30, 40, 48] in mm. Along the sagittal plane at 40 mm and
 413 48 mm for both frequencies the feet of the robot were raising. In the perpendicular plane at 40 mm and
 414 48 mm for both frequencies the overall robot rotated of about 15° and 20°. It was also tried to increase
 415 the frequency for a given amplitude of 10 mm. In the sagittal plane, the robot was able to reach 7 Hz
 416 without falling. In the perpendicular plane at 7 Hz the robot was making violent oscillations (without
 417 falling) reaching mechanical resonance. The trial was subsequently stopped. The results are depicted in
 418 Fig.14. We can clearly see that for the oscillation in the perpendicular plane the increase of total energy is
 419 following an exponential curve, compare to the same experience in the sagittal plane. This clearly shows

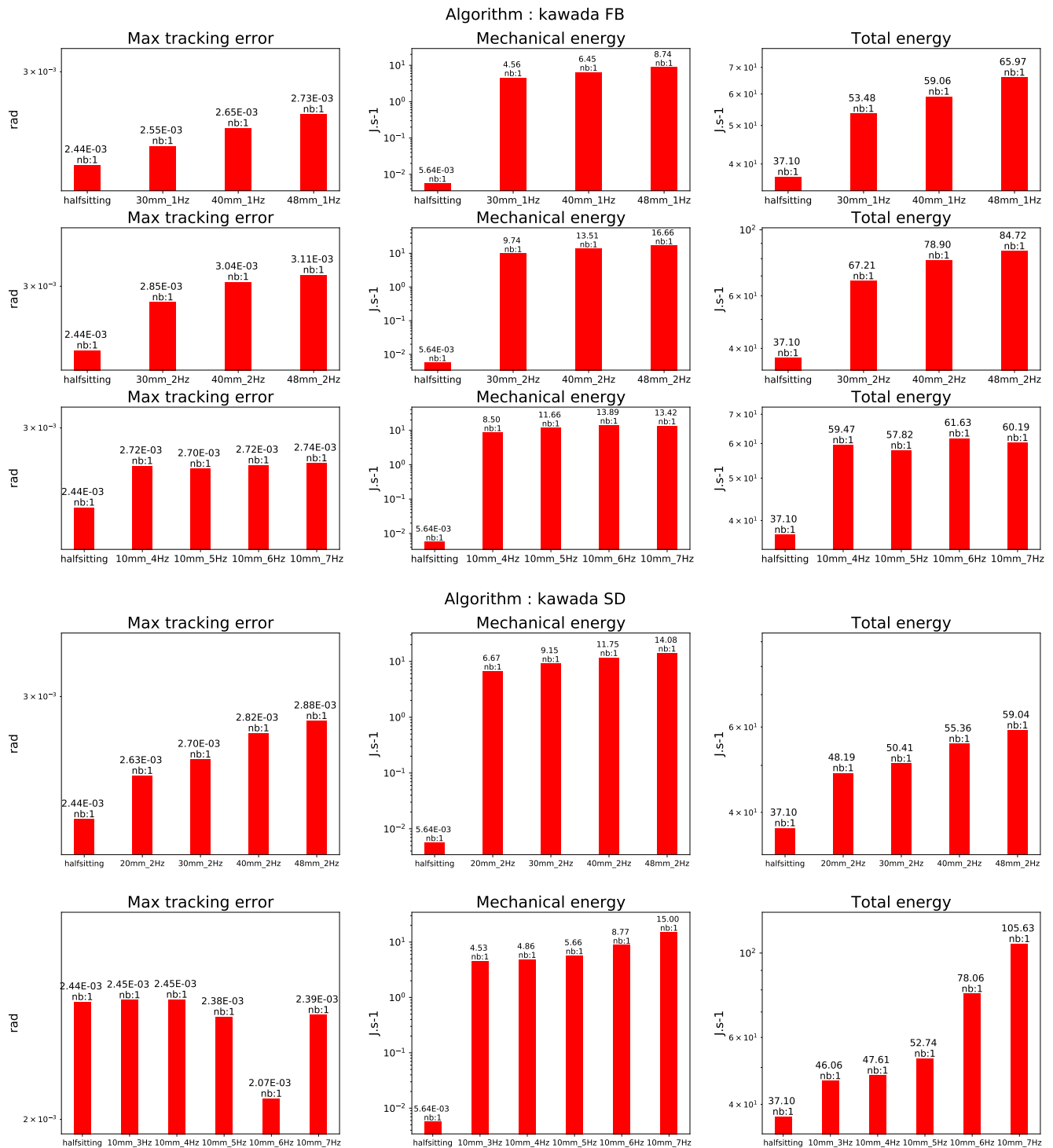


Figure 14. Stabilization evaluation of the algorithm described in Kajita et al. (2007) and Kajita et al. (2001). The upper figure show the results along the sagittal plane, whereas the lower figure depicts the results along the perpendicular plane.

420 that we reach the resonance frequency of the system as it can be seen in the video available at the following
 421 location <https://www.youtube.com/watch?v=djWGs44JmY&feature=youtu.be>.

6 CONCLUSION

6.1 Summary and major outcomes

In this paper we presented a benchmarking for the control architecture such as the one in Fig.1 implemented on the HRP-2 robot owned by LAAS-CNRS. The performance indicator used in this paper are mostly based on Torricelli et al. (2015). Based on this work we computed the following set of KPI:

- walked distance,
- success rate,
- max tracking error,
- duration of the experiment,
- mechanical joint energy,
- actuators energy,
- cost of transport,
- mechanical cost of transport,
- Froude number.

They all represent either the particular characteristics of the experiments or the performance of the control architecture used.

The list of algorithms executed on the HRP-2 robot were:

- a flat ground capable **CDPG** from Kajita et al. (2003a),
- an analytical flat ground capable **CDPG** from Morisawa et al. (2007),
- a non linear flat ground capable **CDPG** from Naveau et al. (2017),
- a multi-contact **CDPG** from Carpentier et al. (2016),
- a **MPWBC** from Koch et al. (2014),
- a **WBC** which is the stabilizer from Kajita et al. (2007) and Kajita et al. (2001)
- a **WBC** that computes the joint position from the end-effector plus center of mass trajectories from Mansard et al. (2009)
- a **WBC** that computes the joint acceleration from the end-effector plus center of mass trajectories used in Carpentier et al. (2016)

The list of environmental conditions where the tests could successfully occur are:

- a temperature controlled room which provided from $10^{\circ}C$ to $35^{\circ}C$,
- a slope of various angles ($[1^{\circ} - 3.0^{\circ}]$),
- a controlled mobile platform that simulates a translating ground,
- a set of calibrated weight from 5 *kgs* to 15 *kgs*,
- a stick with a force sensor on it to apply measured perturbation on the robot,
- different floors with different friction.

The list of the motion performed in the environmental conditions where:

- climbing up 10 *cm* high stairs without handrail,
- climbing up 15 *cm* high stairs with handrail,
- walking over stepping stones,
- walking on a beam,

- 460 ■ walking on a flat ground,
- 461 ■ walking on a slope,
- 462 ■ walking over obstacles.

463 From all these results and experiments few major results come out. First the temperature plays a roll
464 on the energy consumed during a motion. We observed that the colder the room is the more mechanical
465 and electrical energy is consumed. We also noticed that the more the motion is at the limit of stability the
466 more the stabilizer has to inject energy into the system to compensate for potential drift. This create a
467 noticeable increase in energy consumption, e.g. when the robot walk on a beam, step over obstacle, walk
468 on stepping stones. However the most expensive motion is climbing stairs which is clearly a challenge for
469 future potential applications where stairs are involved.

470 Finally in terms of cost of transport, the algorithm proposed by Carpentier et al. (2016) seems to be the
471 most efficient and the most versatile. Its main disadvantage during this campaign was the lack of on-line
472 implementation compare to Morisawa et al. (2007) and Naveau et al. (2017).

473 6.2 Future work

474 We could not properly compute the KPI when we tried to vary the friction of the ground. A future work is
475 then to implement a proper slip observer like the one in Kaneko et al. (2005). Build a stabilizer that could
476 be used in multi-contact in order to compensate for the external perturbation and the modeling assumption.

477 Furthermore, the LAAS-CNRS acquired a new humanoid robot Talos Stasse et al. (2017). The future
478 work consist in implementing all the algorithms presented in this paper and perform the benchmarking on
479 this new robot.

AUTHOR CONTRIBUTIONS

480 OS, EB, KGE conducted the experiments on the temperature, climbing stairs, at the LNE. MN and OS
481 conducted the experiments with Koroibot. OS, EB and PS conceived the research idea. PS obtained funding
482 for the project. OS, KGE, MN, EB, RG, GA and PS participated in the preparation of the manuscript.

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SUPPLEMENTAL DATA

485 As a reminder, a CAD model of the staircase used is available on the github repository where
486 all the log of the experiments are also present: https://github.com/laas/koroibot_KPI. All the
487 computation performed on the logs and implementing the key performance indicators are available here:
488 <https://github.com/laas/EnergyComputation>.

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