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Whole-Body Compliant Dynamical Contacts in Cognitive Humanoids

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Third year project objectives report

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Table of Contents

3.2 Project objectives for the period . . . 7
3.2.1 Overview . . . 7
3.2.1.1 WP1: toolbox for computing and controlling dynamics of whole-body movements with contacts (UB) . . . 9
3.2.1.2 WP2: understanding and modelling human whole-body behaviours in physical interaction (JSI) . . . 9
3.2.1.3 WP3: control and optimization of whole-body motion in contact (UPMC) . . . 10
3.2.1.4 WP4: adaptation, Generalization and Improvement of Compliant Control and Tasks with Contacts (TUD) . . . 10
3.2.1.5 WP5: systems integration, standardization and evaluation on the iCub robot (IIT) . . . 10
3.2.1.6 WP6: management (IIT) . . . 11
3.2.1.7 WP7: dissemination and Exploitation (IIT) . . . 11
3.3 Work progress and achievements during the period . . . 11
3.3.1 Progress overview and contribution to the research field . . . 11
3.3.2 Work packages progress . . . 11
3.3.2.1 Work package 1 progress . . . 13
3.3.2.2 Work package 2 progress . . . 18
3.3.2.3 Work package 3 progress . . . 35
3.3.2.4 Work package 4 progress . . . 43
3.3.2.5 Work package 5 progress . . . 48
3.3.2.6 Work package 6 progress . . . 50
3.3.2.7 Work package 7 progress . . . 51
3.4 Deliverables and milestones tables . . . 54
3.4.1 Deliverables (excluding the periodic and final reports) . . . 54
3.4.2 Milestones . . . 55

A List of dissemination events **60**
A.1 IIT contributions to dissemination . . . 60
A.1.1 Invited talks . . . 61
A.1.2 International events participation . . . 61
A.1.3 Other events . . . 63
A.1.4 Talks at international conferences . . . 63
A.1.5 Pubblications . . . 64
A.1.6 Media coverage . . . 65
A.1.7 iCub at international events . . . 65
A.2 TUD contributions to dissemination . . . 66
A.2.1 Invited talks . . . 66
A.2.2 Pubblications . . . 66
A.2.3 Media coverage . . . 67
A.2.4 MSc. and Ph.D. theses . . . 68
A.2.5 Student research stays . . . 68

A.2.6 Organised conference workshops . . . 68
A.2.7 Invited speakers . . . 68
A.2.8 Collaborations . . . 68
A.3 UPMC contributions to dissemination . . . 69
A.3.1 Invited talks . . . 69
A.3.2 Other events . . . 69
A.3.3 Talks at international conferences . . . 69
A.3.4 Publications . . . 70
A.4 UB contributions to dissemination . . . 70
A.4.1 Invited talks . . . 70
A.4.2 International events participation . . . 71
A.4.3 Talks at international conferences . . . 71
A.4.4 Editorial work . . . 71
A.4.5 Publications . . . 71
A.5 JSI contributions to dissemination . . . 71
A.5.1 Invited talks . . . 71
A.5.2 Editorial work . . . 72
A.5.3 Publications . . . 72
A.6 INRIA contributions to dissemination . . . 72
A.6.1 Invited talks . . . 72
A.6.2 International events organization . . . 72
A.6.3 Other events . . . 73
A.6.4 Talks at international conferences . . . 73
A.6.5 Editorial work . . . 73
A.6.6 Publications . . . 73
A.6.7 Media coverage . . . 74

Index of Figures

1 The IIT CoDyCo team at the Italia's got talent television show. The robot performed the CoDyCo balancing demonstration with recent results on contact switching. 7

2 Screen shots of the replicable simulations of the CoDyCo validation scenarios. These simulations can be replicated on Linux and OsX, downloading and compiling the open-source software available on the CoDyCo software repository. (1) Instruction on how the install the entire software framework can be found here: `https://github.com/robotology/codyco-superbuild`; (2) instructions on how to run the specific demonstration can be found here: `https://github.com/robotology-playground/WBI-Toolbox-controllers`; (3) the scientific paper describing the controller and the software architecture is openly available here: `http://journal.frontiersin.org/article/10.3389/frobt.2015.00006/full`. 9

3 Change of contact force in the vertical direction. The right foot of the iCub is placed on a white foam. 16

4 World reference frame w and local sensor reference frame $\{s\}$. $R(q_w^s)$ denotes the quaternion-based rotation matrix that rotates the world reference frame w into $\{s\}$. 16

5 Robot manipulator control interface consisting of HapticMaster robot and monitor for providing human with visual feedback (right photo). Compliant environment with different stiffness properties (left photo). 20

6 Result of the experiment. Graphs in each column correspond to the stage when the robot was updated. The upper row graphs show the performance of the robot in terms of control of reference position along z axis. The second row shows the error between the reference force and the force produced by the robot. The third row shows the trajectory of motion of robotic manipulator end-effector when the control responsibility was given to human (black line) and when it was given to robot (green line). The influence of local models is shown by blue ellipses and its centres by red crosses. 21

7 A. The ready-made spring model in the Haptic API. B. Block diagram of the compliant force control. The force is rendering based on the end-effector position and the velocity with parameters (spring stiffness and damping factors) in the real time. 23

8 Experimental Design. Two target positions were set: $z = t_1$ for learning session and $z = t_2$ for test trial. 23

9 Experimental visual stimuli. The end-effector and the two target positions ($z = t_1$ and $z = t_2$) were visually indicated on the computer screen. 24

10 The total recording of the completion of the first block. (Subj. 06). **A.** End-effector Z-position, **B.** Z-velocity and **C.** Z-force. **D.** the relationship between the position and the force compared between the force directly measured by the sensor and the force calculated by the equation with the real time z-position and z-velocity. 25

11 Experimental data for one participant (the first block, three test trials). Red lines represent the forces, which were directly measured by a sensor at the end-effector. Blue lines represent the forces, which were calculated in the real time by spring stiffness and damping factor with the end-effector position. . . . 26

12 The averaged end-effector z-position performance in the reaching movements against the linear spring-damper force for 6 subjects. The data were averaged across 3 blocks (9 (Learning + Trial) sessions). The blue lines represent the average performance in the Learning session, and the red in the Test trial, the coloured areas represent their standard error respectively. 26

13 The averaged end-effector z-velocity performance in the reaching movements against the linear spring-damper force for 6 subjects. The data were averaged across 3 blocks (9 (Learning + Trial) sessions). The blue lines represent the average performance in the Learning session, and the red in the Test trial, the coloured areas represent their standard error respectively. 27

14 The averaged end-effector z-force performance in the reaching movements against the linear spring-damper force for 6 subjects. The data were averaged across 3 blocks (9 (Learning + Trial) sessions). The blue lines represent the average performance in the Learning session, and the red in the Test trial, the coloured areas represent their standard error respectively. 28

15 Illustrate averaged time to reach the targets with the comparison between the Learning session (blue) and the Test trial (red) for six subjects. The error bars represents the standard error across the total number of the repetitions. 28

16 Experiments setup for five different positions: (a) stance, (b) wide stance, (c) low handle, (d) middle handle and (d) high handle. A pulley mechanism, which is connected to the subject by a belt, perturbs the subject's CoM. Contact forces are measured at the feet and hands. Motion is recorded with an optical motion capture system. 30

17 An example of the perturbation force applied to the CoM of the subjects. This is for the subject whose body mass is 76.5 kg. The intensity of the perturbation is number 6 meaning that the force is $6/8$ of the maximum for this subject. . . 31

18 Schematic diagram of the planar humanoid robot model. 32

19 Average of the total torque for the subjects at each pose and each perturbation intensity. The stance position required the most torque in order to maintain balance. While the low handle position required the least amount of torque for the same perturbation. 34

20 Example of assembly with iCub. Top: the physical interaction for realizing the assembly and the heat-maps representing the intensity of the contacts in the forearms. Bottom: the trajectory of the hands during the assembly; the joint torques of the right arm. 35

21 Examples of balancing on non-rigid contacts during whole-body task execution. 37

22 40

23 42

24 Perliminary experiment for real-time estimating human whole-body dynamics with distributed accelerometers and force/torque sensors. The technology is the same originally devloped for the iCub, modified to becomes a wearable technology. At present a single IMU and force-plate are used. In this preliminary experiment only ankle and hip torques were estimated. 43
25 Human reaching experiment with target dependent contacts and synchronized arm motions. 45
26 Planning in spkining neural networks with multiple constraints on a Kuka robot. 46
27 48
28 A compliant carpet subject to a uniform force distribution 49
29 The robot balancing on the semi-cylindrical seesaw 50
30 The iCub CoDyCo demonstration at the national television show Italia's got talent. 61
31 Top left: the iCub Veni-Vidi-Vici summer school. Top right: the iCub at the IROS 2015 event organised by the robotics unit at the European Commission. Bottom left: iCub with the piano player, Giovanni Allevi. Bottom right: icub with Matteo Renzi at the "Italian Manufacturing Forum". 62
32 Samples from the comic of Fiamma Luzzati describing the physical human-robot interaction experiments with the iCub (INRIA/UPMC). 75

Figure 1: The IIT CoDyCo team at the Italia's got talent television show. The robot performed the CoDyCo balancing demonstration with recent results on contact switching.

3.2 Project objectives for the period

3.2.1 Overview

The specificity of CoDyCo relies on the fact that the progress beyond the state of the art is guided by the yearly implementation on the iCub humanoid. Within this context, **CoDyCo third year specific objective was to design and implement the control of whole-body posture on compliant (non-rigid) contacts**. This objective poses specific challenges: (1) if all contacts are compliant, suitable posture (i.e. floating-base) estimation strategy is required; (2) if no model of the environment compliance is available, suitable on-line estimation algorithms are necessary; (3) finally, the control of compliant contact wrenches poses specific control challenges (the relative degree increases with respect to the rigid case). To address these challenges, a number of scientific sub-objectives have been defined and achieved during the CoDyCo third year. In work package 1, software tools for environmental compliance estimation and floating base estimation were developed and released with an open-source license. In work package 3, the theoretical control framework for balancing on compliant contacts was developed. In work package 4, models for real-time regression with latent contact type inference have been analysed. In work package 5, two demonstration scenarios have been implemented: balancing on a compliant carpet and balancing on a seesaw.

Beyond the activities to achieve this result, other long term activities have been conducted in preparation for the following years objectives. These activities involve human experiments, software infrastructure maintenance and the development of learning/control algorithms.

Task	IIT	TUD	UPMC	UB	JSI	INRIA	
WP1	0.00	1.00	-	2.18	2.00	2.96	8.14
WP2	-	1	1.20	13.88	21.69	0.52	38.29
WP3	-	9.65	8.79	1.63	2.00	4.03	26.10
WP4	9.79	12	0.74	1.68	3.00	3.30	30.51
WP5	13.06	2	0.14	1.44	-	0.52	17.16
WP6	1.51	1	0.19	-	0.44	-	3.14
WP7	1.00	-	0.11	-	-	-	1.11
	25.36	26.65	11.17	20.81	29.13	11.33	**123.45**

Measures to address reviewers' recommendations

Hereafter we discuss how the CoDyCo consortium addressed the two main recommendations provided as a report of the second year review meeting. The recommendations are reported below in the boxed paragraph.

The members of the consortium have to focus their efforts in integrating all developments achieved in WP2, WP3, and WP4 into the physical robot through WP5. Many control and learning methods have been considered during the last two years. These methods should converge, as much as possible, into a unified global control scheme, which can be shared and disseminated by the consortium.

Integration and unification between different control and learning methods have been pursued with the following activities.

1. UB and TUD implemented state of the art learning algorithms (WP4) for environmental compliance estimation (WP1). The associated learning strategy has been implemented in a learning algorithm which is distributed with an open source license (`https://github.com/azadm/LWR_for_ContactParams`). The estimated model is suitable for the control models proposed in WP3 and coincides with the one to be used in the third year validation scenario (WP5).

2. IIT, UB and UPMC contributed to D3.2 on "Local solver in compliant-world cases" [1]. The document presents two control algorithms, distinguishing between a model-free (UPMC) and a model-based (IIT, UB) approach. On the one hand, the document is an effort to converge to a common approach for mode-based approach. On the other hand, the deliverable underlines the necessity of investigating different approaches when they lead to viable alternatives (model-free versus model based).

3. IIT designed and distributed among partners a document[1] to define a common notation suitable for the CoDyCo scope. The use of a common notation is a prerequisite for comparing different approaches and converging to into a unified global control scheme.

The simulation environment and experimental data are in open source, and this is commendable, but they should be made easier to use.

Dataset and software documentation has been improved. Simulations of the iCub first and second year validation scenarios can be performed on the iCub simulator and on the iCub robot following the given instructions. Experimental dataset are publicly available on `https://db.codyco.eu`.

1. Instructions for compiling the entire CoDyCo software have been improved. The installation procedure `https://github.com/robotology/codyco-superbuild` leverages the YCM `https://github.com/robotology/ycm` which guarantees the integration of multiple projects giving visibility to individual contributions while maintaining the structure of a single global project.

[1] `https://it.sharelatex.com/project/564ddaaf9cec09503ca12023`.

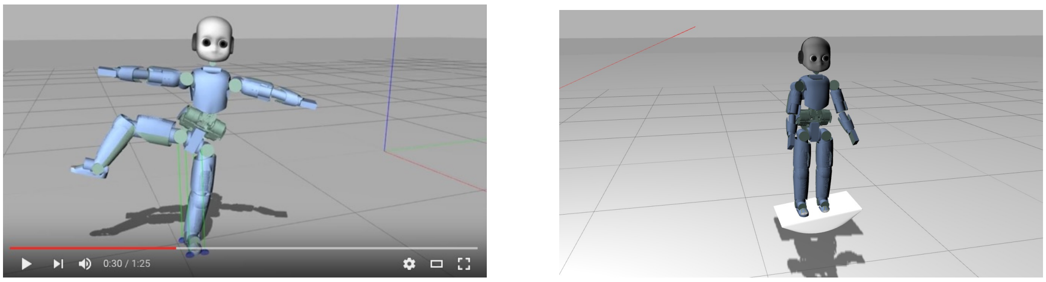


Figure 2: Screen shots of the replicable simulations of the CoDyCo validation scenarios. These simulations can be replicated on Linux and OsX, downloading and compiling the open-source software available on the CoDyCo software repository. (1) Instruction on how the install the entire software framework can be found here: `https://github.com/robotology/codyco-superbuild`; (2) instructions on how to run the specific demonstration can be found here: `https://github.com/robotology-playground/WBI-Toolbox-controllers`; (3) the scientific paper describing the controller and the software architecture is openly available here: `http://journal.frontiersin.org/article/10.3389/frobt.2015.00006/full`.

2. The C++ torque balancing module (first and second year validation scenario) software has been documented and step-by-step instructions for replicating the demonstration in simulation and on the real robot have been optimised based on user feedback (see Fig. 2).

3. The Simulink seesaw torque balancing module (third year demo) has been documented and it can replicated on simulation following the given instructions (see also Fig. 2).

4. Exploiting the available tools for software testing (e.g. Travis `https://travis-ci.com` and RTF `https://github.com/robotology/robot-testing`) a set of routines for continuos installation and testing of the CoDyCo software have been implemented. Testing includes the codyco-superbuild, the OCRA framework and the iDynTree software. These automatic tests guarantee the code consistency and a continuous validation of the installation.

3.2.1.1 WP1: toolbox for computing and controlling dynamics of whole-body movements with contacts (UB) The overall goal of this work package is to develop software libraries and software modules to be used as toolbox by the entire project consortium. Main objectives of WP1 in the third year of the project were (i) to improve the software to be able to cope with compliant contacts within task 1.4; (ii) to continue on extending and enhancing the iDyn library within task 1.5; (iii) to develop a wearable technology for estimating human whole-body dynamics in preparation of the fourth year objectives.

3.2.1.2 WP2: understanding and modelling human whole-body behaviours in physical interaction (JSI) There were two main objectives within WP2 for the third year of the project: (i) to continue the work on designing of models for human whole body motion in contact where we focused on reducing the dimensionality of the actions taken by the human motor control apparatus during predictable (Task 2.2) and unpredictable (Task 2.3) perturbations of human whole-body behaviour; and (ii) to investigate how humans interact with compliant environment, to model how the viscoelastic parameters of the environment are represented by human CNS, and to study the factors involved in generalization and adaptation of skills learnt in contact with the compliant environment (Task 2.4).

3.2.1.3 WP3: control and optimization of whole-body motion in contact (UPMC)

The overall objective of this work package is to provide a control architecture dedicated to humanoid robots involved in personal/service applications, which imply physical interactions, i.e. contacts, with the environment. Such a control architecture is a requirement to bridge the existing gap between state-of-the-art methods in humanoid robots control and real-world applications.

Similarly to year two, the objectives of WP3 for the third year of the project are three-fold. The first one is to demonstrate the applicability of state of the art whole-body motion controllers, such as the one developed in [2] and [3], on the iCub robot in multi-contact, goal oriented scenarii (Task 3.4). The third one is to explore ways to enrich the retained whole-body controllers with the capability to interact with non-rigid environment (Task 3.3). The third one is to keep exploring potential ways of optimally coupling the local, reactive control level and the global, decision making one (Task 3.4). More particularly, the third year objectives include:

- the development of effective methods to deal with non compliant contacts, being them model-based or model free;
- the extension of inverse dynamics learning techniques.

3.2.1.4 WP4: adaptation, Generalization and Improvement of Compliant Control and Tasks with Contacts (TUD)

The goal of WP4 is to endow the CoDyCo humanoid robot control architecture with the core abilities for the adaptation, generalization and self-improvement of both control laws and tasks that involve physical interaction with humans, and the environment. In this context, we propose learning approaches that work in conjunction with the control architecture devised in WP3 and rather complement analytical robotic approaches with on-policy learning than starting from scratch. A core idea behind this work package is that learning should complement classical approaches and not supersede them.

The third year objectives of WP4 include:

- Novel methods for imitation and reinforcement learning of skills with contact will be devised and tested.
- Learning how to combine elementary tasks by imitation and reinforcement learning. The combinations involved include the learned simultaneous use of elementary tasks, the sequential use as well as the co-articulation of tasks.

3.2.1.5 WP5: systems integration, standardization and evaluation on the iCub robot (IIT)

Work-Package 5 has focused on the implementation of the third-year validation scenario. This scenario aims at verifying the control performances in the case the humanoid robot iCub must balance by means of compliant or dynamical contacts (see `https://github.com/robotology-playground/codyco-deliverables/blob/master/D5.3/pdf/D5.3.pdf` [4]).

3.2.1.6 WP6: management (IIT) The third year management was primarily dedicated to the project consolidation. Among the main goals the maintenance of the software repository and database.

3.2.1.7 WP7: dissemination and Exploitation (IIT) The main dissemination objectives for the CoDyCo third year were the website maintenance, the dissemination activities and management of the IPR.

3.3 Work progress and achievements during the period

3.3.1 Progress overview and contribution to the research field

All the CoDyCo third year objectives have been attained. Here is a list of the main CoDyCo third year achievements.

- Release of an open-source software for contact compliance estimation.
- Release of an open-source software for floating-base estimation.
- Models of human interaction with compliant contacts.
- Definition and solution of the theoretical framework for balancing on compliant contacts.
- Learning models of simultaneous use of elementary tasks and co-articulation of multiple tasks.
- Implementation of the third validation scenario: balancing on compliant or dynamical contacts.

3.3.2 Work packages progress

WP1: toolbox for computing and controlling dynamics of whole-body movements with contacts (UB) WP1 objectives were achieved for the third year. In summary, the main accomplishments are:

In T1.3 UPMC developed OCRA "Optimization-based Control for Robotics Applications," a set of software tools to facilitate the development of optimization-based controllers.

In T1.4. UB and TUD developed a framework and software tool for parameter estimation of compliant contacts between the robot and the environment.

In T1.5. IIT developed a YARP, C++ Kalman filter module for singularity-free estimation of floating base position and orientation.

WP2: understanding and modelling human whole-body behaviours in physical interaction (JSI)

In T2.3 JSI studied mutual learning of human and robot in case of interaction with a compliant environment. A novel method for shared control between the human and the robot was developed to efficiently facilitate the robot skill synthesis for the desired interaction.

In T2.2 and T2.4 UB examined how humans learn compliant force dynamics and modulate their whole-body motions to perform goals in contact with compliant environment. Generalization of learnt behavior was tested by examining the motions in environment with different viscoelastic properties.

In T2.2 and T2.3 JSI and UB performed an experimental study to verify the applicability of the manipulability metrics for analyzing postural control in contact with environment.

Finally, in T2.4 TUD and JSI were finalizing the study examining whether supporting contacts in human arm reaching are planned or are an effect of a reactive controller. UPMC and JSI continued with the experimental study to find a global trade-off arising from the interactions between movement time, cost and accuracy.

WP3: control and optimization of whole-body motion in contact (UPMC) After three years of project, the level of achievement of the objectives in WP3 meets the expectations. The main achievements are:

T3.2 The generalized hierarchical control approach has been extended and applied in a quasi-static torque control framework on iCub.

T3.3 The development of model-free (UPMC) and model-based approaches (UB, IIT) for solving the whole-body reactive control problem in the case of compliant contact points has been pursued (with implementation in simulation (UPMC, UB) and on the iCub robot (IIT)).

T3.4 The development of the OCRA (Optimization-based Control for Robotics Applications) software libraries by UPMC.

T3.4 TUD is pusruing its research effort towards inverse dynamics model learning in presence of dynamic contacts.

WP2 JSI and UPMC have explored experimentally and using a computational model the curved movement trajectories observed on diagonal reaching movement.

WP4: adaptation, generalization and improvement of compliant control and tasks with contacts (TUD) In T4.2 TUD and JSI studied the effect of supportive contacts on reaching motions. Through studies in probabilistic models we could show that these supportive contacts predict volitional movements. In ongoing work, we investigate if the derived concepts can be used for robot control. A pre-print was attached to D2.2 and the the paper is in revision at Scientific Reports (Nature Publishing Group). In another, more theoretical study, TUD showed for the first time that spiking neural networks can implement motion planning in continuous spaces. This research was published with Scientific Reports [5].

In T4.4 TUD developed a model-free probabilistic movement primitive framework to learn variable stiffness controller from demonstrations of joint angle trajectories and joint forces. This work was tested in the iCub robot and was presented at an international robotics conference [6]. UPMC continued their research on whole-body controller for humanoid robots. A novel control strategy for concurrently executing multiple tasks was developed. The controller can overcome incompatibilities between the tasks due to conflicting task objectives and was presented at an international robotics conference [7].

WP5: systems integration, standardization and evaluation on the iCub robot (IIT) The third year WP5 activities have concentrated on the third year validation scenario. A complete description of the scenario can be found in "D5.3 Scientific report on validation scenario 3: balancing on compliant environmental contacts." [4] which discusses the technical implementation of the third year validation scenario (see `https://github.com/robotology-playground/codyco-deliverables/tree/master/D5.3/pdf`). With respect to the state of the art the work progress represents a step towards whole-body torque control under postural, contacts and goal-directed constraints. The integration of tactile feedback within the whole-body controller is a peculiarity of the implemented CoDyCo validation scenario and therefore represents yet another step forward with respect to the current state of the art.

WP6: management (IIT) The CoDyCo project continued successfully. Management activities included the definition of a third amendment procedure smoothly organized by the consortium and the project officer. The software repository (`https://github.com/robotology/codyco`) have been significantly improved as clearly documented in the web-based git repository hosting service (`https://github.com`).

WP7: dissemination and exploitation (IIT) Within WP7, CoDyCo third year achievement include: dissemination at relevant academic and industrial events; population of the CoDyCo database to disseminate robot and humans datasets.

3.3.2.1 Work package 1 progress

Software architecture design and evaluation of available open-source software pertinent to the scope of the project. (T1.1) The goal of T1.1 was to agree on a specific software architecture with associated software tools whose specifications, dependencies and interconnections meet the requirements and needs for achieving the goals of the project. The software, which is called `codyco-superbuild`, has been available via github on `https://github.com/robotology/codyco-superbuild` since the second year of the project. Details about the modules of the software are available in deliverables D1.1, D1.2 and D1.3.

Simulator for whole-body motion with contacts (T1.2) The CoDyCo project requires a modular, component-based dynamics simulation software providing numerically stable, computationally efficient and physically consistent simulations of whole-body virtual human(oid) systems in contact with rigid or soft environments. During year three the iCub simulator was further developed, keeping it aligned with the robot development.

Control library for flexible specification of task space dynamics of floating base manipulators. (T1.3) UPMC has developed OCRA which stands for Optimization-based Control for Robotics Applications. OCRA is a set of tools which facilitates the development of optimization-based controllers for robots. At its core there is ocra-recipes, a group of platform independent libraries which can be used to quickly develop optimization based controllers for any robot. Hierarchical, weighted, and hybrid controller schemes can easily be implemented using the ocra-recipes libraries. The generic interfaces provided by OCRA allow different robots to use the exact same controllers. Examples of such implementations can be found for the humanoid robot iCub (ocra-wbi-plugins), and the 7 DoF Kuka LWR (ocra-kdl). OCRA. also allows users to specify high-level objectives via tasks. These tasks provide an intuitive way of generating complex behaviours and can be specified in XML format.

INRIA has developed a Matlab framework for dealing with the automatic learning and optimization of the soft task prioritization for multi-task controllers. The framework learnOptimWBC (`https://github.com/serena-ivaldi/learnOptimWBC`) supports any robot model with a URDF description. Available models include the Kinova Jaco, KUKA LWR and iCub.

System dynamics estimation software. Extension to environmental compliance estimation (T1.4) As a part of this task, UB and TUD developed a framework in order to estimate the parameters of compliant contacts between the robot and its environment. Using this framework, we can predict contact forces in the next instant. Assume that the body which is in contact with a soft surface is labeled with B_c. We characterize the contact surface of B_c by m fictitious contact points on this body. Let $\mathbf{p}_i$ denote the position of the ith contact point ($i = 1, 2, \ldots, m$) in the world frame. Therefore,

$$\mathbf{p}_i = \mathbf{p} + \mathbf{R}\mathbf{r}_i \,, \tag{1}$$

where $\mathbf{p}$ is the position of the origin of the local frame of B_c with respect to the world frame, $\mathbf{R}$ is the rotation matrix of B_c with respect to the world frame and $\mathbf{r}_i$ is the position of ith contact point in the local frame of B_c. So

$$\dot{\mathbf{p}}_i = \dot{\mathbf{p}} + \dot{\mathbf{R}}\mathbf{r}_i = \dot{\mathbf{p}} - (\mathbf{R}\mathbf{r}_i)^{\wedge}\boldsymbol{\omega} = [\mathbf{I}_{3\times 3} \quad -(\mathbf{R}\mathbf{r}_i)^{\wedge}]\mathbf{J}_s\mathbf{v} \,, \tag{2}$$

where $\mathbf{J}_s$ is the Jacobian of the bodies in contact with soft surfaces, $\boldsymbol{\omega}$ is the angular velocity of B_c and $()^{\wedge}$ represents the skew symmetric matrix. We also have

$$\ddot{\mathbf{p}}_i = \ddot{\mathbf{p}} + \ddot{\mathbf{R}}\mathbf{r}_i = \ddot{\mathbf{p}} - (\mathbf{R}\mathbf{r}_i)^{\wedge}\dot{\boldsymbol{\omega}} + (\boldsymbol{\omega})^{\wedge}(\boldsymbol{\omega})^{\wedge}\mathbf{R}\mathbf{r}_i = [\mathbf{I}_{3\times 3} \quad -(\mathbf{R}\mathbf{r}_i)^{\wedge}](\dot{\mathbf{J}}_s\mathbf{v} + \mathbf{J}_s\dot{\mathbf{v}}) + (\boldsymbol{\omega})^{\wedge}(\boldsymbol{\omega})^{\wedge}\mathbf{R}\mathbf{r}_i \,. \tag{3}$$

According to contact mechanics [8] and its applications in robotics [9, 10, 11, 12], there is a non-linear relationship between compliant contact force and the deformation and the rate of the deformation of the surface. However, in order to simplify the model, we assume a locally linear relationship between the change of the contact force and the change of the deformation and its rate. Based on this assumption, we can write

$$\delta\mathbf{f}_i = \mathbf{K}\delta\mathbf{p}_i + \mathbf{D}\delta\dot{\mathbf{p}}_i \,, \tag{4}$$

where $\delta\mathbf{f}_i$ and $\delta\mathbf{p}_i$ are the changes of the contact force and the deformation at the ith contact point, respectively, and $\mathbf{K}$ and $\mathbf{D}$ are 3×3 matrices of the coefficients of stiffness and damping, respectively. By using a linear integration method, we can estimate $\delta\mathbf{p}_i$ and $\delta\dot{\mathbf{p}}_i$ as

$$\delta\mathbf{p}_i = \dot{\mathbf{p}}_i\delta t + \frac{1}{2}\ddot{\mathbf{p}}_i\delta t^2\,, \tag{5}$$

and

$$\delta\dot{\mathbf{p}}_i = \ddot{\mathbf{p}}_i\delta t\,, \tag{6}$$

where δt is the sampling time. Hence, by substituting (2) and (3) into (5) and (6), we will have

$$\delta\mathbf{f}_i = \mathbf{A}_i\dot{\mathbf{v}} + \mathbf{b}_i\,, \tag{7}$$

where

$$\mathbf{A}_i = \frac{1}{2}\delta t^2[\mathbf{K} \quad -\mathbf{K}(\mathbf{R}\mathbf{r}_i)^\wedge]\mathbf{J}_s + \delta t[\mathbf{D} \quad -\mathbf{D}(\mathbf{R}\mathbf{r}_i)^\wedge]\mathbf{J}_s\,, \tag{8}$$

and

$$\begin{aligned}\mathbf{b}_i \;=\; & \delta t[\mathbf{K} \quad -\mathbf{K}(\mathbf{R}\mathbf{r}_i)^\wedge]\mathbf{J}_s\mathbf{v} + \frac{1}{2}\delta t^2[\mathbf{K} \quad -\mathbf{K}(\mathbf{R}\mathbf{r}_i)^\wedge]\dot{\mathbf{J}}_s\mathbf{v} \\ & +\frac{1}{2}\delta t^2\mathbf{K}(\boldsymbol{\omega})^\wedge(\boldsymbol{\omega})^\wedge\mathbf{R}\mathbf{r}_i + \delta t[\mathbf{D} \quad -\mathbf{D}(\mathbf{R}\mathbf{r}_i)^\wedge]\dot{\mathbf{J}}_s\mathbf{v} + \delta t\mathbf{D}(\boldsymbol{\omega})^\wedge(\boldsymbol{\omega})^\wedge\mathbf{R}\mathbf{r}_i\,.\end{aligned} \tag{9}$$

Also for the moment of the contact forces we have

$$\delta\mathbf{n}_i = (\mathbf{R}\mathbf{r}_i)^\wedge\delta\mathbf{f}_i\,. \tag{10}$$

Therefore, total change of the force vector for B_c will be

$$\delta\mathbf{f}_s = \begin{bmatrix}\sum_{i=1}^m \mathbf{A}_i\dot{\mathbf{v}} + \sum_{i=1}^m \mathbf{b}_i \\ \\ \sum_{i=1}^m(\mathbf{R}\mathbf{r}_i)^\wedge\mathbf{A}_i\dot{\mathbf{v}} + \sum_{i=1}^m \mathbf{b}_i\end{bmatrix} = \begin{bmatrix}\mathbf{A}_f \\ \\ \mathbf{A}_n\end{bmatrix}\dot{\mathbf{v}} + \begin{bmatrix}\mathbf{b}_f \\ \\ \mathbf{b}_n\end{bmatrix} = \mathbf{A}\dot{\mathbf{v}} + \mathbf{b}\,. \tag{11}$$

Hence, the estimated (for the next instant) 6D force-torque vector of the contact force of B_c will be

$$\hat{\mathbf{f}}_s = \mathbf{f}_s + \delta\mathbf{f}_s = \mathbf{A}\dot{\mathbf{v}} + \mathbf{b} + \mathbf{f}_s\,, \tag{12}$$

which is a function of contact parameters ($\mathbf{K}$ and $\mathbf{D}$), current force (read from F/T sensors) and joint accelerations ($\dot{\mathbf{v}}$). Note that for the constraints on the soft contact force (unilaterality and friction cone), $\hat{\mathbf{f}}_s$ has to be expressed in the local frame of B_c as $\hat{\mathbf{F}}_s = \mathbf{R}^T\hat{\mathbf{f}}_s$. In order to estimate the contact parameters ($\mathbf{K}$ and $\mathbf{D}$), we use locally weighted projection regression (LWPR) algorithm. This algorithm gives us a locally linear model for a non-linear function which suits our application. The outcome of this algorithm will be $\mathbf{K}$ and $\mathbf{D}$ at each time instant based on the previous values of the contact force and the position and velocity of the contact point. Therefore, we can compute the (estimation of the) contact force in the next instant. Implementation of this algorithm is available from `https://github.com/azadm/LWR_for_ContactParams.git`. To verify this algorithm, TUD performed a few experiments on iCub robot standing on soft surfaces. During those experiments, the robot was standing on two different surfaces (transparent plastic and white foam) while balancing controller was

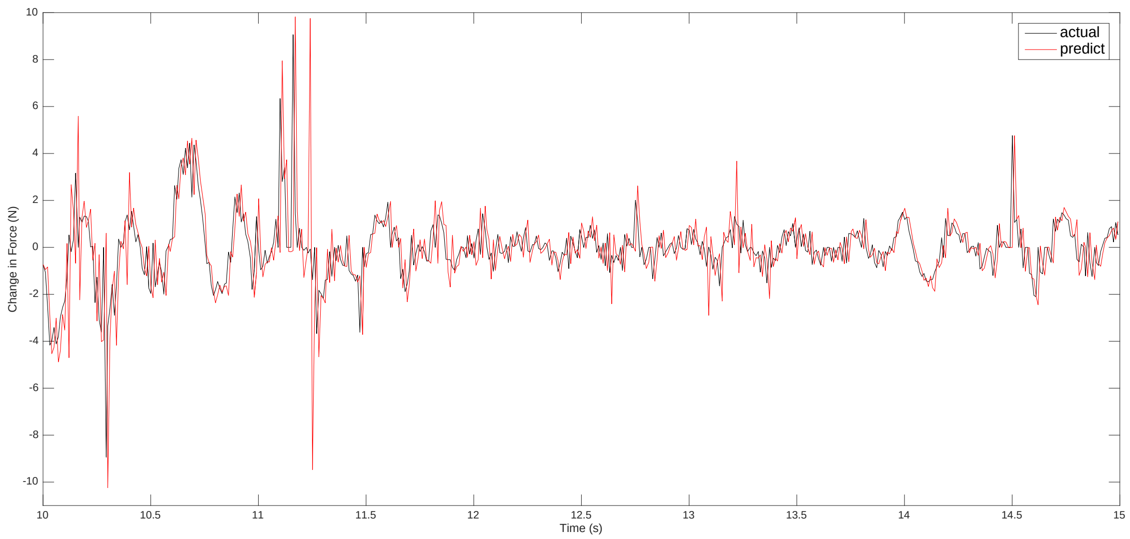


Figure 3: Change of contact force in the vertical direction. The right foot of the iCub is placed on a white foam.

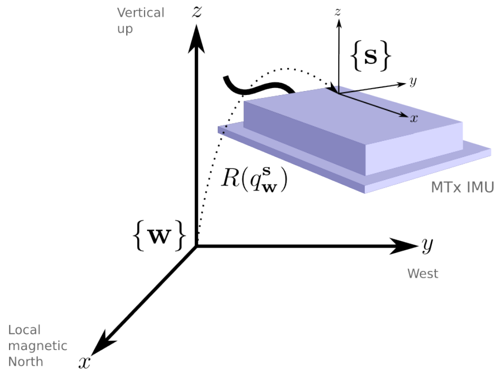


Figure 4: World reference frame w and local sensor reference frame $\{s\}$. $R(q_w^s)$ denotes the quaternion-based rotation matrix that rotates the world reference frame w into $\{s\}$.

running on the robot. The upper body of the robot was perturbed and data from all sensors were collected in order to calculate the movements of the contact points and also the contact forces. By feeding these values into our LWPR algorithm, we estimated the contact force and compared with the actual data from F/T sensors. The results are acceptable and show the consistency of the LWPR estimation algorithm. For example, Fig 3 shows the match between actual and estimated change of the contact force in the vertical direction while the robot's right foot is on a soft surface (i.e. white foam).

Extension and enhancement of the iDyn library. (T1.5) As part of this task, IIT has developed a YARP, C++ based module in charge of implementing a Kalman filter to estimate the floating base position-and-orientation (see `https://github.com/robotology/codyco-modules/tree/master/src/modules/wholeBodyEstimator`).

In particular, the goal of this Kalman Filter is to estimate the orientation of a world reference frame w with respect to the sensor reference $\{s\}$ in the quaternion representation (radians), i.e. q_w^s. The filter uses only a triad of gyroscopes and accelerometers along with a simple model of the process representing solely the orientation to be estimated. In this way, the state of the Kalman Filter will be the quaternion-based orientation of the world w in the sensor reference frame $\{s\}$, i.e.

$$x = q_w^s \tag{13}$$

Where $q = [q_1 \quad q_v]$, $q_1 \in \mathbb{R}$, $q_v \in \mathbb{R}^3$ and $||q|| = 1$.

The (discrete-time) *process model* of the filter is obtained starting off the continuous time equations relating the quaternion orientation with its derivative resulting in the following differential equation:

$$\dot{q}_w^s(t) = \frac{1}{2}\Omega(\omega^s(t))q_w^s(t) \tag{14}$$

Linear approximations of the above dynamics with a fixed-time step assumption leads us to the *process model* of the filter of the form

$$x_{k+1} = Ax_k + w_k$$

The *measurement model* of the filter is constituted by the accelerometer only, neglecting its bias and scaling factors or body acceleration. The latter assumption is also done in many commercial IMUs as the one used to compare our results. This leads us to a measurement model of the form

$$z_k = h(x_{k+1}) + v_k$$

The measurement model described by the above equation is non-linear in q. To fully describe the filter we further need to linearize $h(\cdot)$. Then, we have all the elements necessary to implement an Extended Kalman Filter with linearized measurement equations. For further details see `https://github.com/robotology-playground/codyco-deliverables/blob/master/D5.3/pdf/D5.3.pdf` Sec. 5.1 [4].

Extra: updated crawling module. One exemplifying task for the humanoid robot to deal with multiple switching contacts is the crawling. A first crawling controller was created for Robotcub project. At the VVV15 iCub summer school, INRIA developed a new code to make the crawling demo compatible with the new motor control architecture of the iCub, including the updated dynamics estimation (`https://github.com/serena-ivaldi/iCub_crawling`).

Resources Overall, the use of resources within WP1 was in accordance to the plans.

WP1 person months	IIT	TUD	UPMC	UB	JSI	INRIA
Year 1	8.67	1.00	3.29	0.51	2.00	-
Year 2	3.00	3.00	0.47	2.29	-	-
Year 3	-	1.00	-	2.18	2.00	2.96
Partial	11.67	5.00	3.76	4.98	4.00	2.96
Overall	12.00	9.00	6.00	15.00	6.00	5.00

Deviations from workplan Overall the project is aligned with the plan. UB has been organised next year activity to fully exploit the remaining person months.

3.3.2.2 Work package 2 progress

Shared control method in interaction with compliant environment At JSI we studied mutual learning of human and robot in case of interaction with a compliant environment. A novel method for shared control between the human and the robot was developed to efficiently facilitate the robot skill synthesis for the desired interaction. If the robotic skill is incrementally formed (online) while the physical interaction task is performed/taught by the human demonstrator then the robot has the capacity to generate the control commands for the robot already during the learning stage. However, the human is simultaneously controlling the robot in order to teach it how to perform the given interaction task. Therefore, there can be a conflict between the human commands and commands generated by the currently obtained robotic skill. To solve this issue, an additional method was developed that delegates the control responsibility between the two acting agents in tasks involving interaction with compliant environment.

While shared control is a well-studied subject in case of pure teleoperation [13], only few studies exist in human-in-the-loop robot teaching framework. One of our previous studies [14] focused on developing a shared control method for teaching humanoid robot of compliant whole-body interaction with unpredictable environment in online manner. The control was shared percentually between human and robot based on the average error between the demonstrated actions and the actions from the robot over entire task space up until the current observation time. The disadvantage of this method is that the human cannot efficiently inspect the performance of the currently learnt robotic skill in specific subspace (or state region) of the interaction task. In addition, percentually shared responsibility between the two agents makes it hard for the human to determine who is responsible for a potentially bad performance of the task.

To solve the above-mentioned drawbacks we developed a new method, where the control between the two agents is shared based on the existence of local models in the specific subspace (or state region) of the task. If no local models within the robotic skill exist for a specific subspace, where the task is currently performed, then the control responsibility is given to the human so that he can perform the task through the robot body and at the same time teach it. If local models within the robotic skill exist for the subspace where the task is currently performed, then the control responsibility is given to the robot so that the human can inspect its performance. In case the observed performance is unsatisfactory, the human can update the robot in that specific region. The advantage of this approach is that the skill inspection/correction can be done online (during the demonstration stage) without the need to stop the setup, as opposed to offline robot learning where the skill can be inspected only after the demonstration stage, and if corrections are required the demonstration stage has to be repeated.

The control was shared between the human and the robot as [14]

$$y_{cmd} = C \cdot y_{demo} + (1 - C) \cdot y_{robot}, \tag{15}$$

where y_{cmd} is a vector of commands sent to the robotic mechanism, y_{demo} is a vector of commands given by the human demonstrator, y_{robot} is a vector of commands produced by the current state of robot and $0 \leq C \leq 1$ is a weight factor that determines the influence of each agent. Pure human control is achieved when $C = 1$, and pure machine control is achieved when $C = 0$.

The practical implementation of the proposed method was done based on Locally Weighted Regression (LWR)[15]. LWR is an online machine learning method that approximates the non-linear model of demonstrated skill with a subset of local linear models. Each local linear model is fitted with a receptive field within the state region that determines its domain. The receptive fields are usually realised by a Gaussian kernel functions so that the closer the current input value is to its centre the higher the activation is. In term, higher higher activation of receptive field means higher influence of the corresponding local model on the output prediction. The prediction of output variable y based on some new input variable x is defined by a sum of contribution of all local models, where the models closer to the input variable have higher impact.

In the proposed shared control method the control responsibility between the two agents depends on the activation of the receptive fields of the local models of LWR. If the activation in a given state region is above some predefined threshold w_{th}, sufficient local models exist and therefore the control is given to the robot ($C = 0$) so that the human can inspect its performance. In opposite case, if activation is below w_{th}, no sufficient local models exist and therefore the control is given to the human ($C = 1$) to perform an additional teaching. The method can be expressed as:

$$C = \begin{cases} 0 & \text{if } w_{max} > (w_{th} + \frac{d}{2}) \\ \frac{1+\cos\left(\pi \frac{w_{max} - (w_{th} - \frac{d}{2})}{d}\right)}{2} & \text{if } (w_{th} - \frac{d}{2}) \leq w_{max} \leq (w_{th} + \frac{d}{2}) \\ 1 & \text{if } w_{max} < w_{th} - \frac{d}{2}) \end{cases} \tag{16}$$

where w_{max} is the activation of the model receptive fields [15] and w_{th} is an activation threshold that we introduced to determine the model-proximity based shared control. The switching of responsibility between the human and the robot control is essentially binary to provide the human with a clear feedback about who is responsible for the given task performance. However, we implemented a cosine function to prevent sudden jumps between the two states of responsibility, were d defines the width of switching function.

LWR allows incremental update of local models by feeding a new data point $[x,y]$ each sample time. However, in such case it is hard for human to inspect the robotic skill performance of some subspace of the task as the skill is constantly changing/updating. Therefore we accumulated the training data points for some predefined amount of samples before we fed them to the LWR to update the models:

$$A_{new} = \begin{cases} A & \text{if } C \neq 1 \\ [A; [x, y]] & \text{if } C = 1 \text{ and } length(A) < N_{acc} \\ [\,] & \text{if } length(A) = N_{acc} \end{cases} \tag{17}$$

$$A_{in} = A(randperm(N_{acc}), :) \tag{18}$$

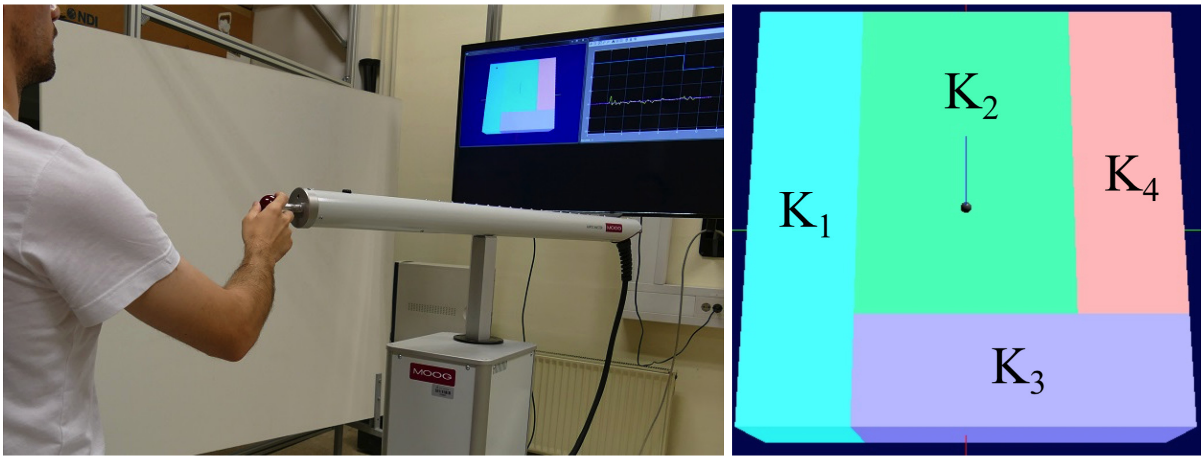


Figure 5: Robot manipulator control interface consisting of HapticMaster robot and monitor for providing human with visual feedback (right photo). Compliant environment with different stiffness properties (left photo).

where A is the training data accumulation buffer and the notation A_{new} indicates that A is updated at each iteration. N_{acc} defines the accumulation length in samples before the new model update is made. Before the data is fed to the LWR the training data in accumulation buffer randomly shuffled in A_{in} buffer.

Experimental validation: We validated the proposed method with the experiments on HapticMaster robot [16]. The experimental setup is shown in Fig. 5 left photo. The task of the robotic manipulator was to interact with a compliment environment in a way to produce some desired interaction force. The environment and robotic manipulator were simulated. We constructed a 0.4 by 0.4 m object so that its surface was in x-y (horizontal) plane of the reference frame, where different sections had different stiffness properties. See Fig. 5 right photo for configuration of the object stiffness properties. The parameters were set $k_1 = 100$ N/m, $k_2 = 150$ N/m, $k_3 = 300$ N/m and $k_4 = 500$ N/m. The robotic manipulator had to produce a desired force $F_z = 100$ N along z axis (vertical), which was perpendicular to the object surface. The necessary interaction force control policy was defined as:

$$F_z = K(x, y)(z_r - z_a), \tag{19}$$

where F_z is the interaction force acting between the manipulator and the object surface, $K(x, y)$ is the stiffness of the object in z axis, z_a is actual and z_r is reference position of the manipulator's end-effector in z axis. When the manipulator was on the softer section of the object surface (i.e. lower stiffness K), the reference position had to be put deeper inside the object to produce the desired force. In opposite case, when the manipulator was on the harder section of the object surface (i.e. higher stiffness K), the reference position had to be put closer to the surface to produce the same desired force.

The results of the experiment are shown in Fig. 6. The top row shows the acquired models (robotic skill) for manipulator's displacement of reference position from the actual position in z axis. Each column represents the different stage of training data update. The time stamps of the update application are displayed on the top. The middle row shows the force prediction error of the obtained models at each stage. The bottom row shows the motion of the robot

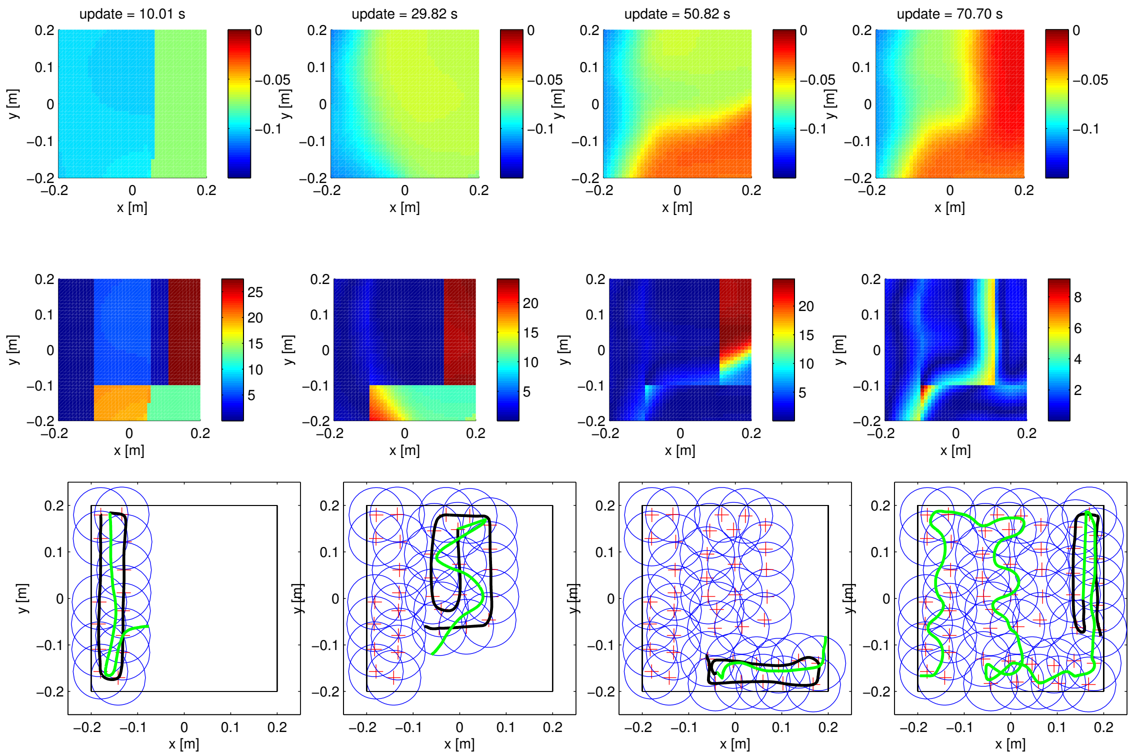


Figure 6: Result of the experiment. Graphs in each column correspond to the stage when the robot was updated. The upper row graphs show the performance of the robot in terms of control of reference position along z axis. The second row shows the error between the reference force and the force produced by the robot. The third row shows the trajectory of motion of robotic manipulator end-effector when the control responsibility was given to human (black line) and when it was given to robot (green line). The influence of local models is shown by blue ellipses and its centres by red crosses.

manipulator (thick black and green line) on the surface of the object (thin black rectangle). The black line shows the trajectory when the demonstrator had the control over the robotic manipulator's force production task. The green line shows the trajectory when the robot had the control over the robotic manipulator's force production task. The red crosses show the centres, while blue ellipses show the threshold activation ranges w_{th} of the currently available local models that are part of robotic skill.

Human motor control learning during compliant interaction with environment In this study performed at UB we aimed to examine how humans learn compliant force dynamics and modulate their whole-body motions to reach anticipated goals. Here, we present an experimental idea to measure the goal-directed movements against compliant forces, and then illustrate the ongoing results which were conducted for a few human subjects. At this pilot stage, we are focusing on the simple linear compliant case and discuss further experiments. To deepen understanding of the mechanism in humans, it would be beneficial to develop the humanoid robot control in interacting with multiple compliant surfaces.

Introduction: Humans can learn how to control their own body movements in an uncertain environment, and utilise it to predict the consequences of actions and to achieve a behavioural goal [17, 18]. A considerable amount of research has shown the human capabilities of generalization in visuomotor learning and has been exploring the underlying mechanisms [19, 20]. A certain exposure to a new physical environment facilitates to generalize the spatial and temporal characteristics of the point-to-point movements via error-based learning and perturbation paradigm. In the real-world interactions, there are varied and complicated force dynamics (i.e., governed by not only simple linear principles) when making a contact with an object and handling it. The optimal functions seem to be perceptually learned via repetitive movements against the force. However, to our knowledge, little is still known about how humans can generalize the compliant force dynamics itself and utilize it to their future motor plan.

The CoDyCo project has been investigating the whole-body coordination mechanisms in arm reaching movements and the postural balance control in assistive contact with rigid and/or compliant surfaces. Like humans, robots are required to flexibly adjust their posture and to coordinate the physical mobility with augmented autonomy. We expect that humans could generalize the force principles in a cognitively robust way via force-feedback from the early stage of the body movements. To explore the generalization mechanism of the force dynamics in humans and to model it would provide a useful strategy in humanoid robot control. The successful model could be exploited to effectively control autonomous robots' whole-body balance in interacting with the environment through supportive contacts.

In a pilot study, we focused on a simple case: linear compliant force. We employed a haptic device, Haptic Master (Moog, Inc.), which is controlled by a set of a computer programmes to render robotic manipulandum for force feedback. The pilot experiment measured the end-effector movements controlled by human subjects and analysed the dynamic properties of the movements against the compliant force and the performance.

Modelling: In general, spring-damper force ($\mathbf{F}$) is formulated by the position and the velocity with parameters: spring stiffness (k) and spring damping factor (λ). Here, it is simplified for one direction ($\mathbf{Z}$).

$$\mathbf{F} = k\mathbf{Z}^n + (\lambda \mathbf{Z}^p)\dot{\mathbf{Z}}\,. \tag{20}$$

We employed the ready-made spring model in the Haptic API, where the compliant force formula was assigned to the device, the Haptic Master. The compliant force was rendered by the end-effector position and the velocity with the parameters in real-time (Fig. 7).

Experimental design: As a pilot study, we employed a simple linear spring-damper formula:

$$\mathbf{F} = k\mathbf{Z} + \lambda\dot{\mathbf{Z}}\,. \tag{21}$$

The compliant force formula is assigned to the model in the Haptic Master. Aiming to simplify analysing the performance, the forces and the movements were constrained in the only one direction, here, in the vertical (Z) direction to the ground.

Human subjects learned a spring compliant force via repetitive reaching movements to the first target ($z = t_1$) in a certain period of time, - so called "Learning session". Then, they were asked to move the end-effector to the second, or test, target ($z = t_2$), which was set more far from the t1 position, as a test trial; so, more force would be required for this movement (Fig. 8). In order to achieve the t_2 target, the participants would exploit their prior knowledge of

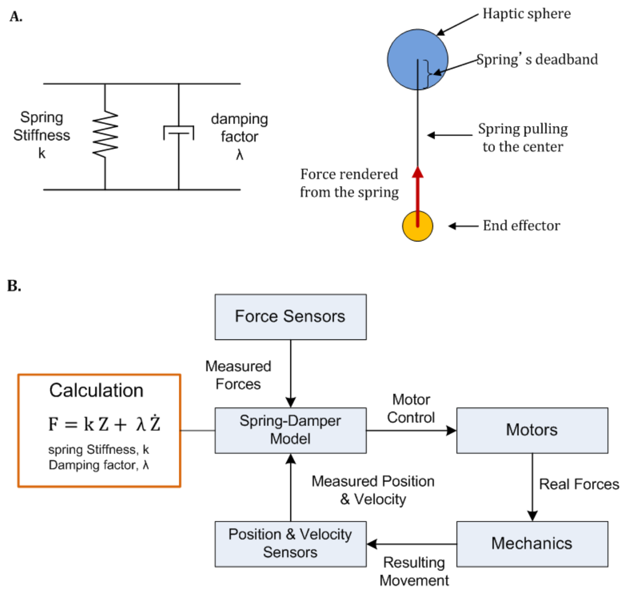


Figure 7: A. The ready-made spring model in the Haptic API. B. Block diagram of the compliant force control. The force is rendering based on the end-effector position and the velocity with parameters (spring stiffness and damping factors) in the real time.

the force dynamics experienced via learning session. We will evaluate whether and how the motion performance is likely to follow the formula previously learned.

Apparatus and Stimuli: The haptic device, "Haptic Master" consisted of a large robotic rod with an end-effector. The "Home" position, where was the centre of the end effector is $z = 0$ at the workspace, was 110 cm from the ground. The spring position was set at $z = 0$. In this study, the rod movements were restricted in the vertical direction only.

The visual information about the task was provided at the computer display to human subjects. The computer screen was located at the right side of the Haptic Master from the subjects; where the centre of the screen was approximately 80 cm from the centre of the robotic rod. The screen was approximately 1 m away from the participants' standpoint, and 80 cm away from the centre of the end effector position. The screen displayed the target

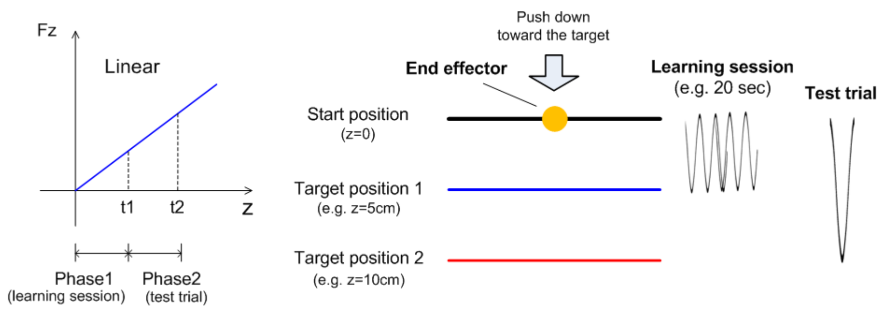


Figure 8: Experimental Design. Two target positions were set: $z = t_1$ for learning session and $z = t_2$ for test trial.

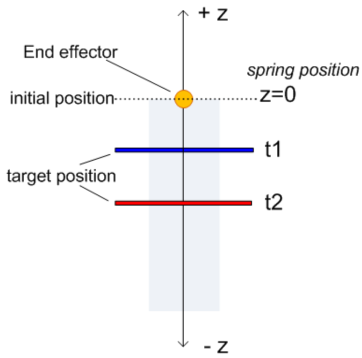


Figure 9: Experimental visual stimuli. The end-effector and the two target positions ($z = t_1$ and $z = t_2$) were visually indicated on the computer screen.

position and the end-effector position in real-time (Fig. 9). The target positions were set at $z = t_1$ (50 mm for learning), and $z = t_2$ (100 mm for test).

Participants: Six male subjects (age: 28.8 +/- 3.1 (SD), height: 175.3 cm +/- 7.1 (SD), weight: 79.5 kg +/- 17.8 (SD), one left-handed) voluntarily participated in the pilot experiment. All had normal or corrected to normal vision, and they had no known motor deficits and/or any limb injuries (self-reported). They were recruited from the student and staff population at University of Birmingham. (One was not nave to the purpose of the experiment.)

Procedure and analyses: Participants stood in front of the haptic device and grasped the end-effector. Firstly, they conducted a practice session followed by the main blocks. They were required to make repetitive movements against compliant force generated by the device to learn the kinetic principle. The movements were monitored by visual information on the screen. Participants pushed the end-effector to reach the target position, and then released the end-effector to allow it to freely return to the initial position (z=0). They were asked to set the centre of the end-effector position on the target as accurate as possible.

The main block consisted of two parts: Learning session and Test trial. In the Learning session, the target position was set at $z = t_1$, described above. Participants controlled the end-effector by their own timing, or rhythm, per each movement in the current pilot study (the specific time windows were not set up by the programme for the series of movements: i.e., push the end-effector down from the start position and reach the target position). The visual feedback was given when the end-effector reached to the target; the target colour indicated this by changing from blue to yellow. Participants learnt the compliant force dynamics by the repetitive movements. he experimenter monitored the elapsed time using a stopwatch, and verbally informed the end of the session when 20 seconds passed. Participant stopped their repetitive movements immediately and prepared for the trial session.

In the Test trial, participants moved the end-effector to the target (coloured red line, $z = t_2$) three times based on the formula they previously learned. In this phase, no visual feedback in the relationship between the end-effector position and the target was given to the subjects.

One block consists of three sets (Learning session + Test trial). Participants conducted three blocks; so, 3 blocks in total, and 9 test trials. Under the current settings, the experiment

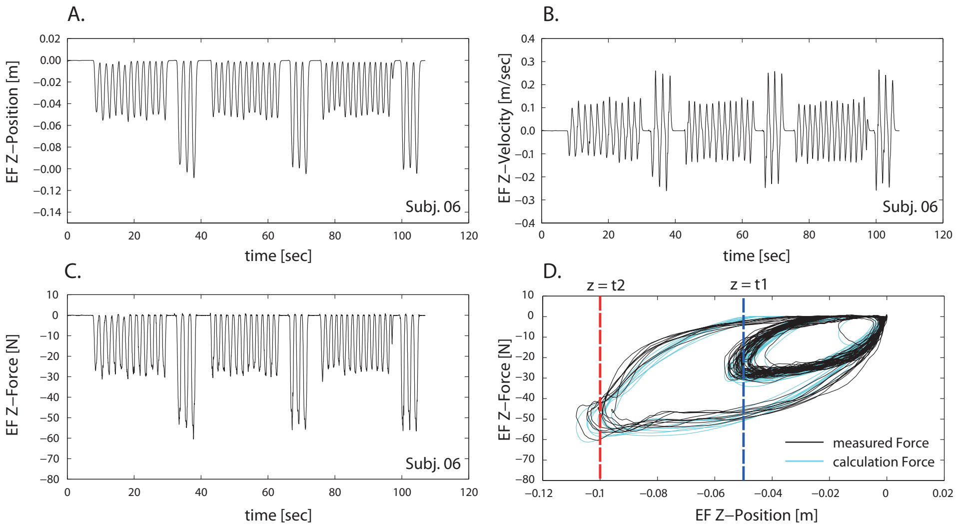


Figure 10: The total recording of the completion of the first block. (Subj. 06). **A**. End-effector Z-position, **B**. Z-velocity and **C**. Z-force. **D**. the relationship between the position and the force compared between the force directly measured by the sensor and the force calculated by the equation with the real time z-position and z-velocity.

was completed within approximately 20 minutes on average.

The dynamic properties of the point-to-point movements were measured: the end-effector's position ($\mathbf{Z}$), the velocity ($\dot{\mathbf{Z}}$), and the force ($\mathbf{F}_Z$) across the time. These were recorded by the 20 msec sampling rate and the properties were analysed and compared between the linear and the non-linear force conditions.

Results: The end-effector position, velocity and force were recorded. Here, illustrates the one participant's one block performance, as an example (Fig. 10).

In order to examine the each reaching movement, the data were extracted from the total between the start ($z = 0.01m$) and the end (approx. $z = t_2$) positions, where the end-effector was released to return to the initial position. These points were determined by calculating the each inflection point (Fig. 11).

The data were averaged across three blocks; one block consisted of three (Learning + Trial) sessions; so participants ideally completed 9 sessions in total, but one (subj.03) accidentally completed only two blocks because of the setting errors. The averaged numbers of repetitions were 152.8 +/- 45.6 (SD) in the Learning session and 27.2 +/- 6.1 (SD) in the Test trial. All six participants' averaged data (the end-effector position, velocity and force) can be seen from Fig. 12 to Fig. 14.

Discussion: Figure 15 showed that some participants (e.g., Subj.01, Subj.06) performed to reach the target position ($z = t_2$) much faster than the expected time duration, which was estimated from the linear equation. That is, the t_2 position was double distance of the t1 from the start position; so the reaching time would be estimated close to the double. The time would not be able to calculate by the simple linear calculation because the damping factor depends on the velocity, though.

This might be caused by the experimental design; that is, participants made the repetitive movements with their own rhythms at the learning session. Because they tend to keep their

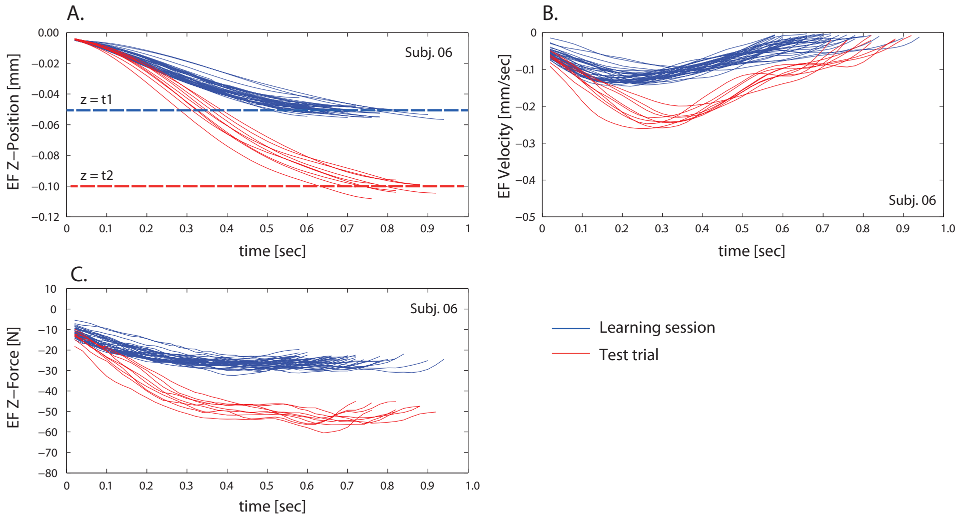


Figure 11: Experimental data for one participant (the first block, three test trials). Red lines represent the forces, which were directly measured by a sensor at the end-effector. Blue lines represent the forces, which were calculated in the real time by spring stiffness and damping factor with the end-effector position.

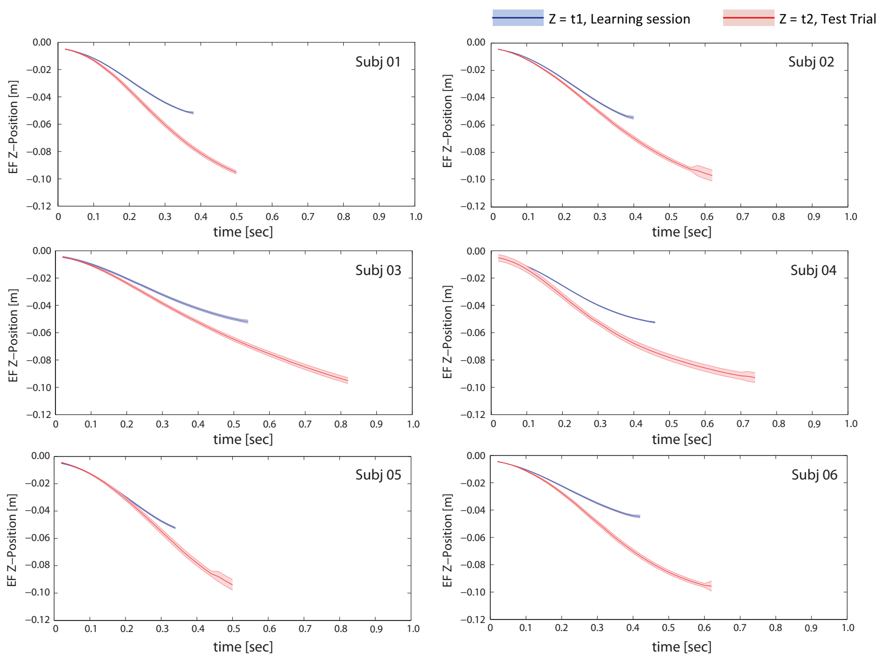


Figure 12: The averaged end-effector z-position performance in the reaching movements against the linear spring-damper force for 6 subjects. The data were averaged across 3 blocks (9 (Learning + Trial) sessions). The blue lines represent the average performance in the Learning session, and the red in the Test trial, the coloured areas represent their standard error respectively.

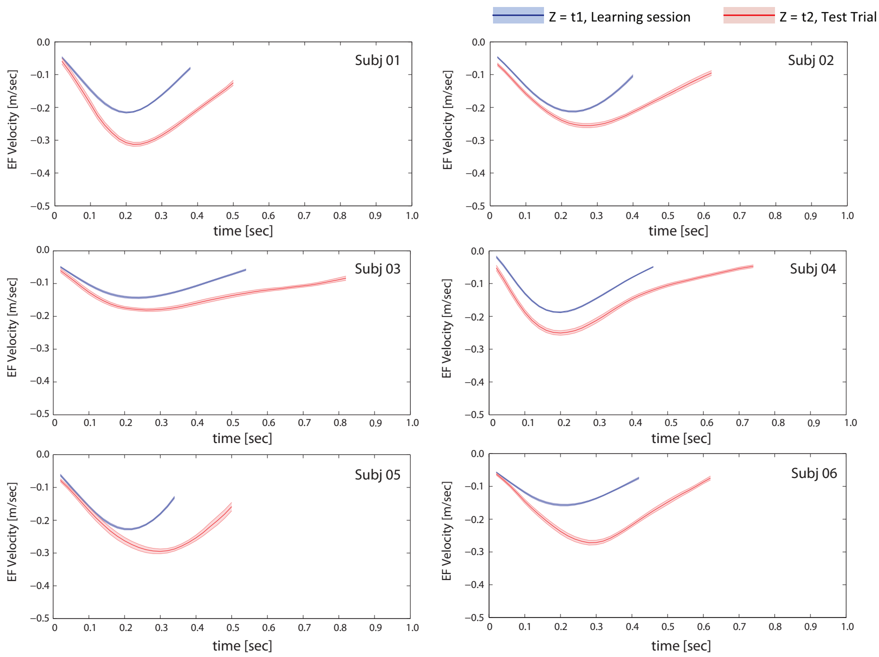


Figure 13: The averaged end-effector z-velocity performance in the reaching movements against the linear spring-damper force for 6 subjects. The data were averaged across 3 blocks (9 (Learning + Trial) sessions). The blue lines represent the average performance in the Learning session, and the red in the Test trial, the coloured areas represent their standard error respectively.

rhythms even in the consecutive trial session, and then they might have unconsciously increased the force or accelerated their speed to reach the target. This possibility can be seen at their movement profiles (Fig. 13: velocity and Fig. 14: force). Several studies have shown that time perception plays an important role in human motor control [21, 22]; therefore, this timing issue should be carefully considered into the experimental design and should avoid any confounding factors. To do this, we will visually guide the participants' movements with a certain time-windows in the future experiment.

Moreover, in the current pilot experiment, the judgment of reaching the target was inaccurate. Although the participants received the visual feedback at the learning session, it only indicated the end-effector crossed the target position, and also there were no task reward. The inaccuracy would have affected their force perception and movements [22] therefore, in the next experiment, we will set a specific correct zone visually defined by a more accurate way (e.g. the similar size of sphere of the end-effector) as the target instead of the line indicators. The task completion in the Learning session would be determined by their performance and individual learning level would be evaluated by their correct movements.

The current analyses conducted for all performance in the test trial (reaching the target ($z = t_2$) three times for each), but the performance might have needed to be evaluated focusing on the first trial only, because the first movement was directly affected by the learning session and the second and the third movements were gradually contaminated.

Overall, through the pilot experiment, we have learned the importance of the timing issue in interacting with compliant surface. We will improve the experimental design and strictly

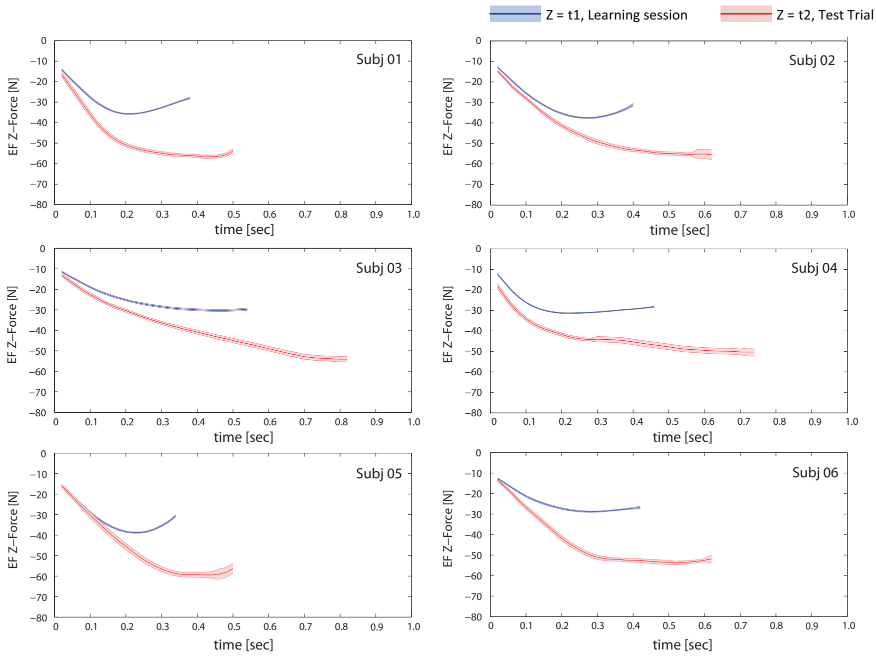


Figure 14: The averaged end-effector z-force performance in the reaching movements against the linear spring-damper force for 6 subjects. The data were averaged across 3 blocks (9 (Learning + Trial) sessions). The blue lines represent the average performance in the Learning session, and the red in the Test trial, the coloured areas represent their standard error respectively.

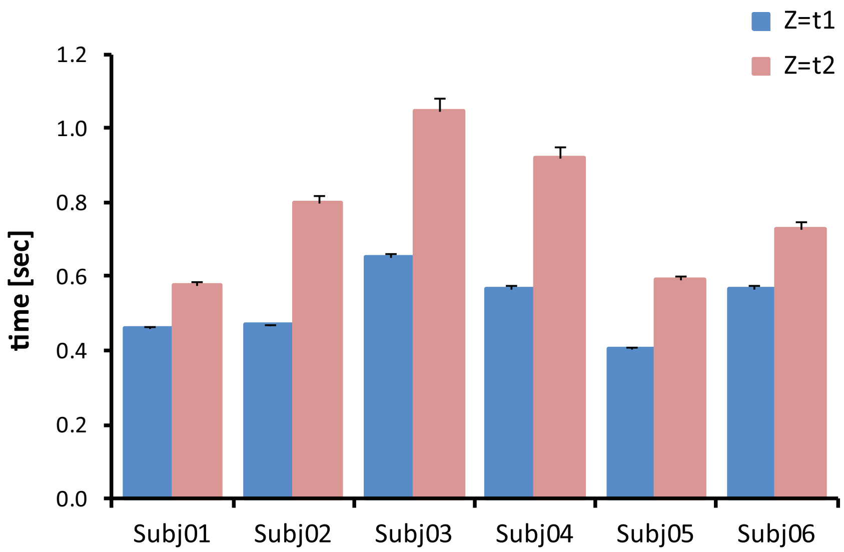


Figure 15: Illustrate averaged time to reach the targets with the comparison between the Learning session (blue) and the Test trial (red) for six subjects. The error bars represents the standard error across the total number of the repetitions.

control the parameters (timing, speed, and the accuracy).

In the future experiment, based on the linear case, we will measure the pattern under the non-linear compliant forces and examine the human goal-directed performance. Besides, as well as the spring-damper, it may help the understanding of the generalization if we employ another compliant force model (e.g. object surface).

Experimental validation of CoM manipulability metric (Task 2.2 & Task 2.3) After the introduction of a set of metrics for studying, analyzing and measuring the ability of humans and humanoids to balance, we performed an experimental study to verify the application of this metrics for human postural control in contact with the environment. In the experiments, the posture of human subjects were perturbed in different configurations and joint torques were computed by inverse dynamics calculations. We demonstrated that the metric is suitable for comparing different postures in the sense of the total required effort for the maintenance of balance.

Human experiments: To verify the application of the *change-of-velocity—unit joint impulse* ellipsoid for human studies, we performed experiments on human subjects. As already mentioned, this ellipsoid can be used to measure torque efficiency in balancing motions. So, in the experiments, we perturbed the CoM of the subjects (by a cable-pulley mechanism) in different configurations and measured the contact forces/moments with force/torque sensors (see Fig. 16). Then we calculated the average total torque that was done by the subjects at each configuration and compared them with the results of manipulability analysis. These steps are described in the following subsections.

Methods: Eleven healthy male subjects participated in this study. Their average age was 21.7 years (SD = 2.2 years), height = 183 cm (SD = 4.6 cm) and body mass 76.8 kg (SD = 8.1 kg). The subjects were informed about the course of the study prior to their participation and were required to sign an informed consent approved by the National Medical Ethics Committee (No. 112/06/13).

We observed the subjects reactions to the external perturbations in five different poses. In the first pose (*stance*), subjects were standing straight with their feet together and arms crossed over the torso (Fig. 16.a). In the second pose (*wide stance*), subjects were standing with their arms crossed over the torso and their left foot 60 cm ahead of their right foot (ankle to ankle distance). In the third pose (*low handle*), subjects were standing as in the first pose and holding the handle which was located in front of their bodies at the hip height (Fig. 16.b). In the fourth pose (*middle handle*), subjects were standing as in the first pose and holding the handle which was located in front of their bodies at the shoulder height (Fig. 16.c). In the last pose (*high handle*), subjects were standing as in the first pose and holding the handle which was located in front of their bodies and above the head (Fig. 16.d).

The subjects were perturbed by a horizontal external force produced by our force-controlled pulling mechanism [23] at the approximate position of their CoM [24]. The command signal was a step with 0.5 second width (see Fig. 17). The actual perturbation force was controlled by a combination of a feed-forward and a PID feedback controller. We selected eight linearly increasing magnitudes of perturbation forces where the maximum was defined as 22% of the individual subject's body weight and the minimum was $1/8$ of the maximum force (increasing rate of $1/8$ of the maximum). Between each perturbation we induced a random pause. For each pose, we repeated the series of eight perturbations ten times (80 trials per subject per

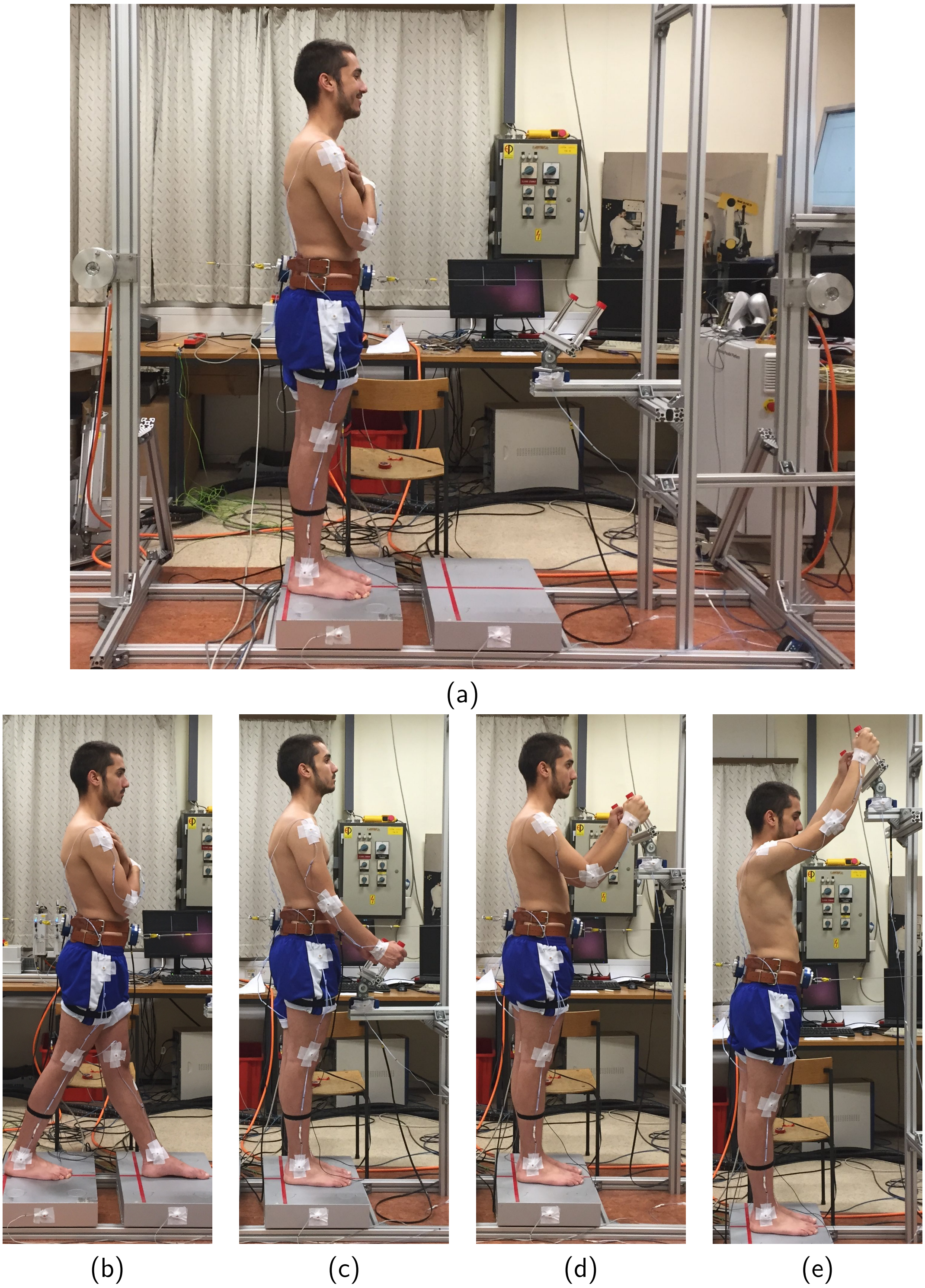


Figure 16: Experiments setup for five different positions: (a) stance, (b) wide stance, (c) low handle, (d) middle handle and (d) high handle. A pulley mechanism, which is connected to the subject by a belt, perturbs the subject's CoM. Contact forces are measured at the feet and hands. Motion is recorded with an optical motion capture system.

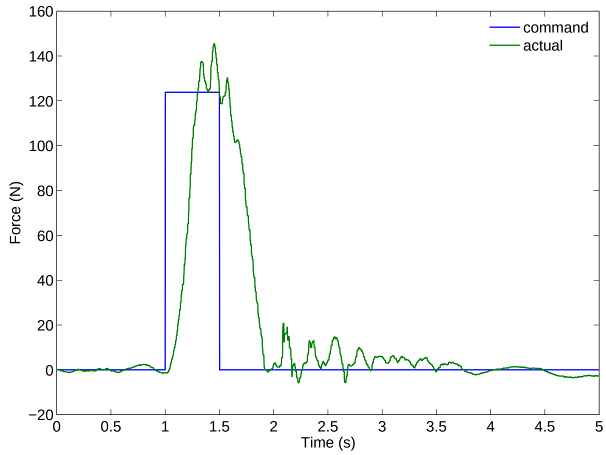


Figure 17: An example of the perturbation force applied to the CoM of the subjects. This is for the subject whose body mass is 76.5 kg. The intensity of the perturbation is number 6 meaning that the force is $6/8$ of the maximum for this subject.

pose) and observed the human reactions. We gave the subjects 10 minutes pause between each pose. In case of the first pose, the subjects had to step before the maximum perturbation was reached. When the subject made a step, the experimenter stopped the procedure and moved to the next series of perturbations. The step was not required in other poses and the series of perturbations repeated uninterrupted.

Body movements were measured by a motion capture system (3D Investigator™ Motion Capture System, NDI, Waterloo, Ontario).The optical markers were placed on the ankle, knee, hip, shoulder, elbow and wrist. The positions of the markers are used to calculate the joint angles. We used two force plates (9281CA, Kistler Instrument AG, Winterthur, Switzerland) to measure the ground reaction forces and center of pressure position. The handle was mounted on a 3-axis force sensor (45E15A, JR3, Woodland, USA) to measure the force between the handle and the subject.

In order to estimate the starting time of the subjects' reactions, we measured muscle activation in Triceps Brachii, Soleus and Tibialis Anterior by surface electromyography (EMG). We placed surface EMG electrodes (SX230 EMG sensor,Biometrics Ltd, Newport, UK) on the selected muscles in accordance with SENIAM recommendations [25]. We also placed a monitor in front of the subject to provide visual feedback on the CoP position that allowed him to move back to the initial pose after each perturbation.

Model: In the experiments, in order to produce movements which are planar only, we prevented applying out-of-plane forces/moments to the subjects by providing a pair of handles for them and perturbing them in a plane. Therefore, we could use planar models for both inverse dynamics and CoM manipulability calculations. Although, using a planar model for wide stance pose is a bit unrealistic. Planar humanoid models that we used for the stance, wide stance and all three handle poses are shown in Fig. 18. These models consist of multiple links which are connected to each other by actuated revolute joints. Note that lower legs are connected to the ground. This is because we assume that the feet of the subjects do not move during the experiments. To model the stance pose, we lock the DoF of the arms. So, in this case, the model has 3 DoF and is unconstrained. For the wide stance, the robot has 6 DoF

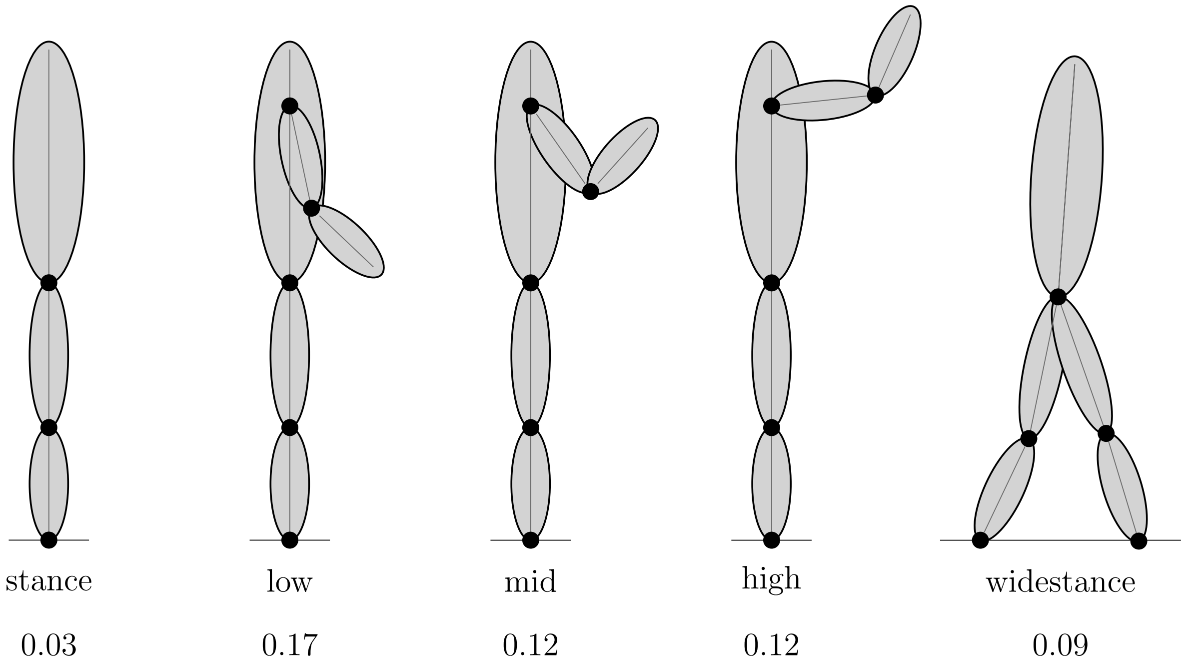


Figure 18: Schematic diagram of the planar humanoid robot model.

and is constrained due to the kinematic loop in the legs. For the handle poses, the robot has five actuated DoF and it is constrained at the hand to model the handle contact.

Since for balancing we are only interested in movements in the horizontal direction, we calculated the maximum value of $\Delta\dot{\mathbf{c}}$ in this direction for all five positions. This represents the maximum achievable change of velocity of the CoM in the horizontal direction and is a measure for the ability to accelerate the CoM in order to correct its position in this direction. Joint angles of the arms for the handle positions are set to the average initial joint angles of the subjects that we calculate from the marker positions. For the low handle, the shoulder angle (angle between torso and upper arm) is 12° and the elbow angle (between upper and lower arms) is 145°. Shoulder and elbow angles are 35° and 77° for the middle handle, and 96° and 118° for the high handle positions, respectively. For the wide stance position, we assume zero angles in the knees and upright torso. The weighting matrix that we use for the calculations is a diagonal matrix as

$$\mathbf{W} = diag([2.33, 3.45, 4.55, 1, 1.25])\,, \tag{22}$$

which is determined to include the differences in the joint's strengths [26, 27, 28, 29].

Calculated values for the maximum $\Delta\dot{\mathbf{c}}$ for the five positions are mentioned in Fig. 18. As it can be seen in this figure, the low position has the highest value (i.e. 0.17) for the manipulability and the stance position has the lowest one (i.e. 0.03). Manipulability for the middle and high positions are the same (0.12) and lower than the low position. Also wide stance manipulability (i.e. 0.09) is only better than the stance position. Therefore, according to the manipulability analysis for our models, we expect the same ranking for the five positions in the sense of total average required torque to keep the balance. We will verify this hypothesis in the next subsection.

Results: As already mentioned, inverse dynamics are used to compute the torques that are applied (at the joints) by the human subjects. Joint angles are calculated by using marker positions, and joint velocities and accelerations are estimated by using simple time differentiation. Lengths and inertial parameters of the subjects are calculated via the software that is introduced in [30]. Featherstone's Spatial software package [31] is used for the dynamics calculations.

To work out the average total torque for each position and each perturbation intensity, first we calculate the joint torques from inverse dynamics for each trial (in total 4400 trials $= 5$ poses $\times 8$ intensities $\times 10$ reps $\times 11$ subjects). Then we calculate the average torque over the reps for each joint. Note that, since maximum achievable torque of the arm joints vary with arm configuration, we normalize shoulder and elbow torques for the handle positions [26, 27, 28, 29]. Then, we sum up the normalized joint torques to get 440 (i.e. 5 poses $\times 8$ intensities $\times 11$ subjects) values for the average normalized joint torques. The beginning time is the subjects' average initial reaction time which is estimated by the average EMG signal. The end time is roughly the time that the subjects have recovered from the perturbations.

The means of the normalized joint torques (per subjects) is shown in Fig. 19. This figure shows the total average torque (after removing outliers) for all subjects at each configuration and each intensity. The lines are fitted to the values by using least squares method. The standard error of the means are also shown in this figure. As can be seen in this figure, the low handle pose has the lowest total torque and the stance pose has the highest. According to this graph, the ranking between the positions is 1) low, 2) middle, 3) high, 4) wide stance and 5) stance. This ranking is more visible in higher intensities and it conforms with the manipulability numbers from our analysis. The only difference is that manipulability analysis predicts that middle and high positions are the same whereas experimental results show a bit difference between two (middle is better than high). Therefore, the experimental results agree with the manipulability analysis in the previous subsection. Configurations of greater manipulability require less torque, in order to maintain balance after perturbations of equivalent magnitudes.

Conclusion: A set of metrics are introduced in this chapter to study, analyse and measure the ability to balance for humans and robots. These metrics, which are called the manipulability of the center of mass, provide two types of ellipsoids which graphically show how the CoM can be accelerated in 3D space by a certain amount of change of motion (due to impulses) at the joint space. These ellipsoids can be used to measure torque efficiency and maneuverability of humans and robots. The proposed metrics are applicable to floating base robots with non-breakable contacts with the environment. Also, experiments on human subjects are performed to investigate the applicability of the proposed metrics for human studies. In the experiments, the standing subjects (in five different configurations) were perturbed by a controlled force acting on their CoM. Then, the selected configurations were ranked according to the average total torque that is applied by the subjects to recover their balance at each configuration. It is shown that the proposed metric for torque efficiency can successfully predict the same ranking between the configurations as the experimental results suggested. This agreement shows the applicability of the metrics for human studies as well. Therefore, manipulability of the center of mass provides greater insight into the posture controllability of humans and robots, in various configurations and contact conditions.

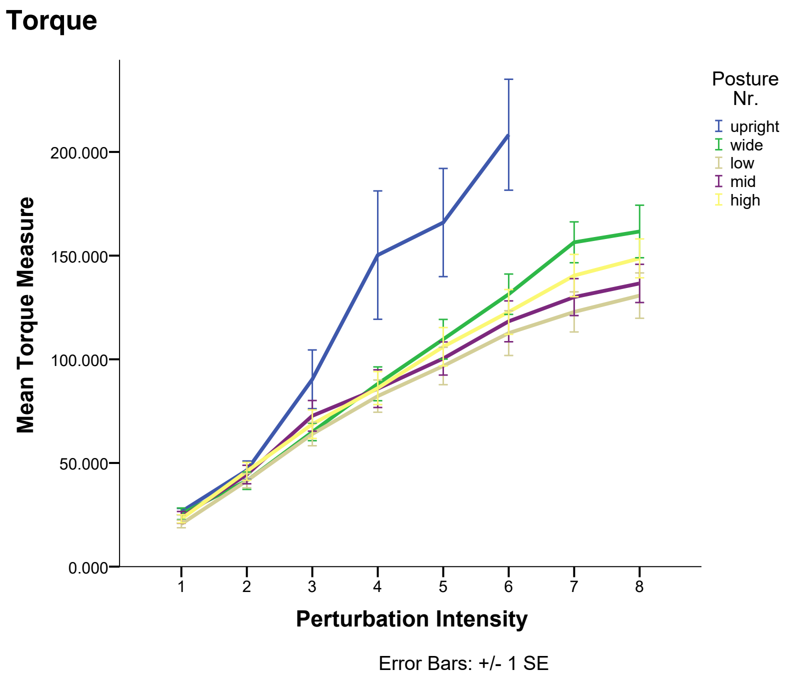


Figure 19: Average of the total torque for the subjects at each pose and each perturbation intensity. The stance position required the most torque in order to maintain balance. While the low handle position required the least amount of torque for the same perturbation.

Characterization of human-robot interaction during cooperative assembly INRIA studied the characterization of human-robot interaction during a cooperative assembly task between the iCub and 56 healthy adults (36,95 $\pm$ 14,32 years old, 19 males, 37 females) without or with little prior expertise in robotics. The experiments were performed in UPMC. The dataset includes tactile data from the forearm of the iCub, estimated contact locations and forces, arm joint trajectories. At first, INRIA conducted an analysis of the most remarkable signals for the social interaction, namely joint gaze and speech, to study if the dynamics of such signals is influenced by some individual factors, such as extroversion and negative attitude towards robots. In [32], we reported our results: we found that the more people are extrovert, the more and longer they tend to talk with the robot; and the more people have a negative attitude towards robots, the less they will look at the robot face and the more they will look at the robot hands where the assembly and the contacts occur. On the other hand, the analysis of the cumulated forces and moments exchanged by the humans reveals that the cumulated forces are very similar for all the participants regardless of their individual factors: we did not find a significant correlation between the cumulated contact forces and the extroversion, negative attitutde towards robots, nor with the expertise in robotics or the participant's age. More thorough analysis are ongoing, in preparation for an article. Interestingly, when we interviewed the participants after the experiment, we found out that they were generally not afraid to touch the robot, but only after a demonstration of contact shown by the experimenter: without this "proof of feasibility" most of them reported that they would have never dared to touch the robot for collaborating with it.

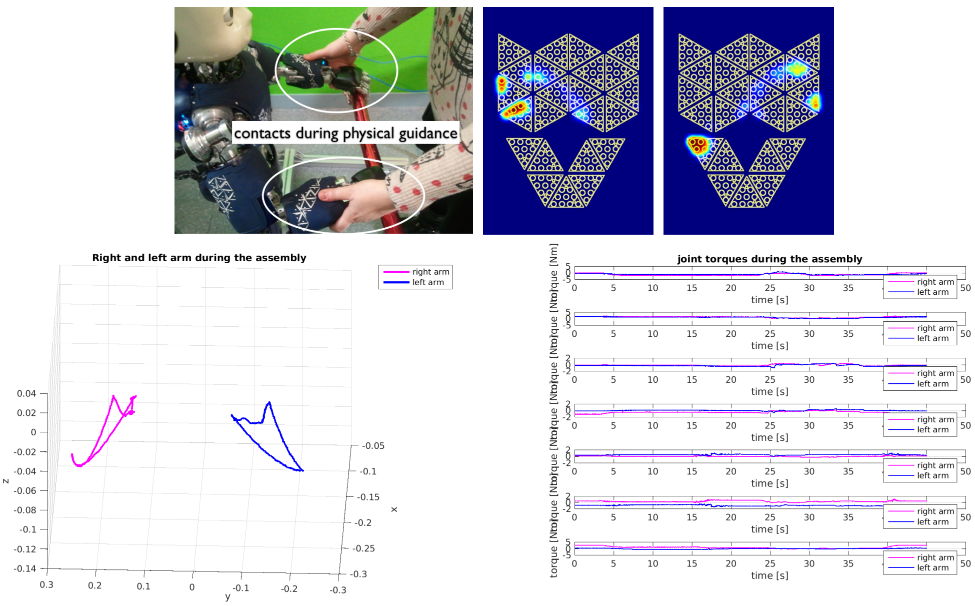


Figure 20: Example of assembly with iCub. Top: the physical interaction for realizing the assembly and the heat-maps representing the intensity of the contacts in the forearms. Bottom: the trajectory of the hands during the assembly; the joint torques of the right arm.

Resources Overall, the use of resources within WP2 was in accordance to the plans. There was an increase in the amount of PM for JSI due to the fact that we could not find a suitable Post-doc but hired a PhD student instead. Consequently we foresee approximately 25% increase in total amount of PM at the end of the project. UB is below what has been planned but next year activities have been re-planned accordingly.

WP2 person months	IIT	TUD	UPMC	UB	JSI	INRIA
Year 1	-	-	0.28	2.64	18.80	-
Year 2	-	3.00	0.48	7.67	21.85	-
Year 3	-	1.00	1.20	13.88	21.69	0.52
Partial	-	4.00	1.96	24.19	62.34	0.52
Overall	-	4.00	1.00	45.00	55.00	1.00

Deviations from workplan No significant deviations.

3.3.2.3 Work package 3 progress The progress for each task in WP3 is described hereafter.

Formulating the control problem (T3.2) During year 2, a generalized projector has been developed by UPMC and used in [33] for hierarchical control. The novelty of hierarchical control algorithms based on the use of this generalized projector is that they can handle not only a single standard lexicographic hierarchy as the HQP and weighting strategies do, but also a complex priority network of hierarchies with both strict and non-strict priorities. The priority between each pair of tasks can be handled separately. Only one swapping phase is needed to move an arbitrary number of tasks to their desired priority levels concurrently. Moreover, this generalized projector improves the smoothness during hierarchy rearrangements, because it can regulate to what extent a lower-priority task is projected into the null-space of higher-priority tasks (e.g. completely, partially, or not at all). In [33], the generalized projector is implemented in an optimization based dynamic control framework, which is applied to control a KUKA LWR robot in [34]. However, the application of this control framework in real-time control of humanoid robots is limited, because its computational cost is sensitive to the number of tasks and the number of DoF of the robot.

The aforementioned generalized projector has also been extended and applied in a quasi-static torque control framework on humanoid robots. Compared with the control framework used in [33], the computational cost of this quasi-static framework is much less sensitive to task numbers or robot complexity. This makes it possible to handle a complex network of task priorities by using the generalized projector, with a computation cost that can be suitable for real-time control of humanoid robots. This work has been experimented on iCub at UPMC and the corresponding results are published in [35]. Experiments demonstrate that both motion and contact force tasks of different priorities can be handled by this approach. Task priorities can be maintained and switched, and the switching duration can be adjusted to achieve smoother hierarchy rearrangement.

UPMC also started a study in order to evaluate the role, with respect to balance robustness, of a task explicitly aiming at regulating angular momentum to zero in QP-based whole-body controllers. The obtained results are still preliminary but tend to show, in simulation, that the explicit presence of such a task does not improve the robustness of balance. This work may be further explored during year four.

Solving the local control problem (T3.3) During year 3, UPMC, UB and IIT worked on solving the whole-body reactive control problem in the case of compliant contact points (see Deliverable 3.2 [1] and Deliverable 5.3 [4] for completeness).

UPMC finalized the work on the model-free approach retained during year 2. Indeed, when robots evolve in partially known environments, model-based control approaches requires to incrementally, through experience, modify existing models or build new ones (see Deliverable 4.2 [36] for details on learning of tasks with multiple contacts by imitation and reinforcement learning). While models evolve, the robot still needs to be able to act accordingly, or at least without failure, in this, partially known, environment. Providing an adaptive control approach, not relying on a compliance model, in order to adapt the whole-body motions of humanoid robots to unknown rigidity properties of the environment is thus of interest.

The work contribution of UPMC, following this model-free approach, was published in [37] and is dedicated to whole-body balancing, and more generally whole-body control, with non-rigid, unilateral, frictional support contacts, for example, standing on a soft ground, or pushing against a compliant support contact with one hand while reaching for an object far away with the other hand (see Fig.21). The problems of the manipulation of compliant objects and the handling of unexpected disturbance forces are beyond the scope of this work. Moreover, the

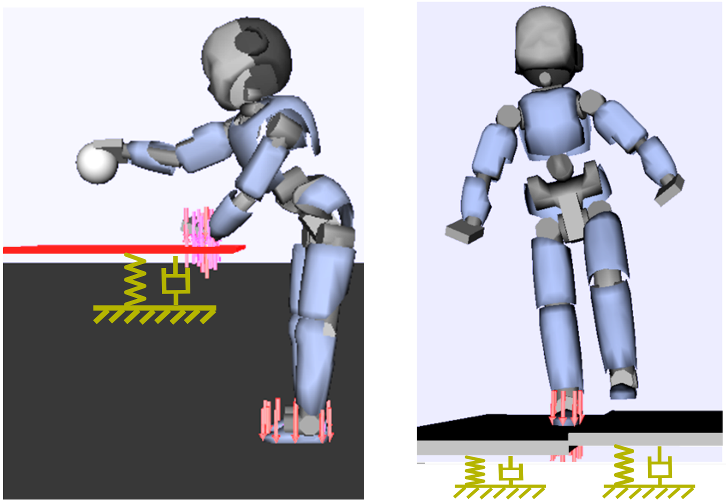


Figure 21: Examples of balancing on non-rigid contacts during whole-body task execution.

proposed control approach does not handle anticipatory aspects of balance, but it provides a reactive mechanism to maintain balance while multiple motion and contact tasks are being performed in a compliant environment.

The contribution of this work consists in a reactive controller for whole-body balancing of humanoid robots performing whole-body tasks in unknown compliant environments. As the motions and forces at support contacts are related to whole-body task executions, their reference trajectories are unavailable a priori. Therefore, this approach focuses on the regulation of contact forces in a reactive way. It reacts to the motions of non-rigid contacts in real-time during whole-body movements, with the aim of establishing contact equilibrium quickly.

A frictional non-rigid contact model is proposed both for simulation and for control. The model parameters of the non-rigid environment are unknown to the controller. The force regulation approach does not try to estimate the impedance parameters of the environment, but it regulates contact forces by reacting to environment motions directly. This reactive control approach is embedded in an optimization based multi-task controller of type (1), which has been used to achieve whole-body control of humanoid robots in rigid environments. However, the reactive principle of the approach proposed here is general and can also be applied in many other whole-body controllers to handle non-rigid support contacts. UB followed the model-based approach they had started to derive during year 2. Indeed, when a model of the environment is available or has been incrementally learnt, using this model does not only provide the necessary adaptation to the new conditions but allows to obtain efficient behaviors that could not be obtained otherwise. It thus makes much sense to try to model the compliant environment.

When dealing with compliant contacts, modifications are induced in the equation of motion and kinematic constraints expression. The former writes

$$M(q)\dot{\nu} + C(q,\nu)\nu + G(q) = B\tau + J_{rigid}^{\top}(q) f_{rigid} + J_{comp}^{\top}(q) f_{comp}, \tag{23}$$

while the latter is decomposed in two sub-equations

$$J_{rigid}(q)\dot{\nu} + \dot{J}_{rigid}(q)\nu = 0 \quad (24a)$$

$$J_{comp}(q)\dot{\nu} + \dot{J}_{comp}(q)\nu = \ddot{p}_{\mathcal{C}_{comp}}, \quad (24b)$$

where $J^{\top}_{rigid}(q)$, f_{rigid}, $J^{\top}_{comp}(q)$ and f_{comp} respectively represent the contact Jacobian in the rigid contact directions, the associated rigid contact wrench, the contact Jacobian in the compliant contact directions and the associated compliant contact wrench. Without loss of generality, contacts are here supposed to be either strictly rigid or compliant[2]. $\ddot{p}_{\mathcal{C}_{comp}}$ is the compliant contact points linear and angular acceleration which is assumed to be a function of the state of the contact points and of the derivative of the compliant contact wrench[3] $\ddot{p}_{\mathcal{C}_{comp}} = z\left(p_{\mathcal{C}_{comp}}, R_{\mathcal{C}_{comp}}, \dot{p}_{\mathcal{C}_{comp}}, \omega_{\mathcal{C}_{comp}}, \dot{f}_{comp}\right)$.

The Newton-Euler equation for the floating-base system, written at the center of mass of the system, can be written

$$\begin{pmatrix} m(\ddot{x} - g) \\ \dot{H}_{\omega} \end{pmatrix} = \underbrace{\sum_{k=1}^{n_c} \begin{pmatrix} 1_3 & 0_{3\times 3} \\ S(p_{\mathcal{C}_k} - x) & 1_3 \end{pmatrix} f_k}_{X_{\mathcal{C}} f} \quad (25)$$

where m is the total mass of the system, $x \in \mathbb{R}^3$ is the position of the center of mass expressed in the inertial frame, $\dot{H}_{\omega}$ is the derivative of the angular momentum, g is the acceleration induced by gravity expressed in the inertial frame, $p_{\mathcal{C}_k}$ is the k-contact point and $S(u) \in \mathbb{R}^{3\times 3}$ is the skew-symmetric matrix such that $S(u)v = u \times v$, where $\times$ denotes the cross product operator in $\mathbb{R}^3$.

From the modified model, it can be shown that f cannot be considered as an independent intermediate control input any longer as its evolution is subject to the contact points dynamics which is a function of $\dot{f}$. $\dot{f}$ becomes the new independent intermediate control input and it can be concluded that compliant contacts augment the relative degree of the controlled outputs. This means that Equation (25) has to be differentiated in order to relate $\dot{f}$ to the desired center of mass behaviour. The computed contact force derivative can then be fed into Equation (24b). Assuming that a good measurement of the compliant contact forces is available and that z can be estimated with high bandwidth and precision through measurement, whole-body dynamics estimation and/or contact model parameters estimation, one can then directly solve the whole-body control problem.

Even if not formulated in this way, this is the approach retained by UB in [38] where a "practical" implementation is proposed. The proposed controller regulates both linear momentum and angular momentum about the center of mass of the robot by controlling the contact forces at soft contact surfaces[4]. Assuming that contact forces at the compliant surfaces are known (i.e. via force-torque sensors) at the current instant, desired contact

[2]A given contact point can actually be rigid in some direction while compliant in other orthogonal ones.

[3]As an intuition, consider the example of a mono-dimensional spring-damper system described by the scalar relation $f = K(x - x_0) + b\dot{x}$, the contact point acceleration can be written $\ddot{x} = \frac{1}{b}(\dot{f} - K\dot{x})$.

[4]rigid contact can be accounted for as well without modifying the proposed method itself and with the advantage of easing the estimation of the state of the floating base

forces at the rigid contacts are calculated in order to provide the required rate of change of the robot's momentum. However, since compliant contact forces are functions of surface deformations, there is not any control on them at the current instant. Nonetheless, it is possible to control those forces in the next instant by controlling the acceleration of the contact points. This can be done by predicting one step ahead in time the compliant contact forces given the currently measured ones and the contact model z. To implement the proposed method in practice, stiffness and damping coefficients of the contact model have to be estimated beforehand by using contact model parameter estimation methods such as in [39], [40], [41] (see section 3.3.2.1).

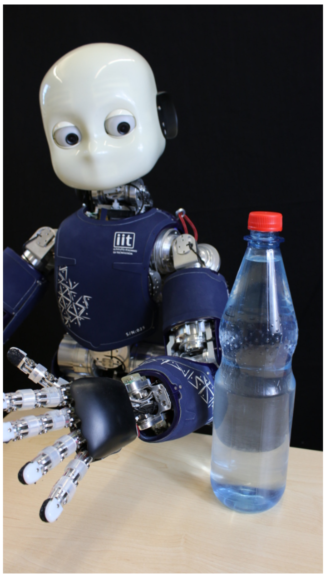
The contribution of IIT on model-based approaches for dealing with compliant contacts is based on the fact that, in practice, assuming that a good measurement of the compliant contact forces is available and that z can be estimated with high bandwidth and precision through measurement is an illusion. Force measurements are subject to high-frequency noises which in practice limits the bandwidth of the available signal. Moreover, the estimation of the contact model z is complex, and subject to many uncertainties.

There are actually many type of soft terrains that exert forces and torques not only depending on their relative compression, but also on the robots joint torques. In these cases, the soft terrain is subject to some rigid constraints that may allow the control of the robot's momentum through the external forces, which thus depend on the joint torques. This is the case of a thin, highly damped carpet, which can be modelled, in the first approximation, as a continuum of vertical springs. Each of these springs is assumed to compress vertically only, and the other degrees of freedom are rigidly constrained, thus creating the aforementioned relation between external forces and joint torques. This brings us back to the case of rigid contacts even though the compliant force component f_{comp} in Equation (23) still needs to be properly compensated for. This particular component cannot be measured separately from the rigid component and a contact model is still needed to estimate it. This approach is the one retained for the demonstration of Year 3 and it is described in details in Deliverable 5.3 [4].

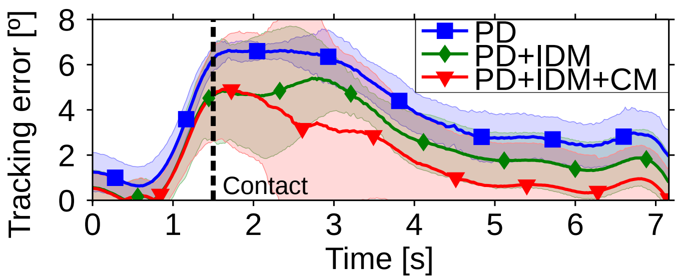
Bootstrapping and validating the control approach in rigid world and compliant cases (T3.4) In order to ease the deployment of QP-based whole-body controllers, UPMC has put together a set of software libraries named OCRA (Optimization-based Control for Robotics Applications). A short description and links to OCRA are provided in the section dedicated to WP1.

Regarding the use of Model Predictive Control in order to handle the problem of postural balancing under varying contact conditions, the work of N. Perrin *et al.* on two simple and novel approaches to solve for 3D locomotion with multiple non-coplanar contacts has been published in [42].

During the third year, TUD continued their research in inverse dynamics model learning in presence of dynamic contacts. We extended the work from the second year [43] by integrating the learned models into a controller on the iCub robot. We evaluated the performance of our mixture-of-contacts approach on real-world tasks such as compensating for contacts with unknown dynamics objects. An exemplary task is illustrated in Figure 22a when an unexpected obstacle is introduced along the trajectory followed by the arm. In Figure 22b can be seen the tracking error in presence of an unknown obstacle for multiple control schema. It can be noticed how making use of the learned contact models improve the performance compared to simple PD controller or PD plus inverse dynamics. A paper was published in an international robotics conference [44].



(a) The robot during an arm movement encounter an unexpected obstacle. Using the learned contact model the robot compensates for the effects of the obstacle.



(b) Tracking error using various control schema. Using the learned contact models improve the tracking performance.

Figure 22

In addition, TUD developed a low-cost sensor glove for tele-operating the iCub. The construction and first imitation learning results of object grasping and manipulation were presented in a workshop [45]. A description of an improved version of the glove with an in-built IMU and separate sensors for proximal and distal joints was submitted to an international robotics conference.

INRIA, in collaboration with TUD, has been working on the problem of bootstrapping multi-task controllers with suitable task parametrization. In [46], INRIA proposed a simplified multi-task controller based on a linear combination of regularized elementary tasks, where the task weights profiles are parametrized functions that can be automatically optimized offline. The control framework has been applied to the real Jaco Kinova arm and to a simulated KUKA LWR arm. The description of the learning and optimisation process for the task priorities is detailed in the section relative to WP4.

Extra results in WP2/WP3: UPMC and JSI collaboration UPMC and JSI have been collaborating in order to try to explain curved movement trajectories observed on diagonal reaching movement. This works originates from the study of JSI to elucidate the computational mechanisms of human motor control in situations when humans seek for a supportive hand contact. Within the framework of this study, researchers at JSI performed a series of human experiments where the subjects had to perform diagonal arm reaching to targets of different sizes. Human reaching studies often focus on reaching forward in the sagittal plane, which commonly results in straighttrajectories [47]. However, slightly curved reaching trajectories were also observed [48], [49]. Reported curvatures were very small, possibly due to small movement amplitudes. JSI investigated whether large amplitude movements outside of the sagittal plane show larger deviations from straight line trajectories.

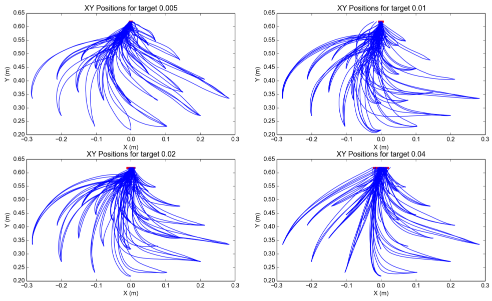
Ten healthy, seated males (20 ± 2.7 years) reached with their dominant right arm to a virtual target using a haptic manipulator, which constrained the motion to the horizontal plane at shoulder height and emulated a uniformly viscous media. The virtual target (width $5mm$) was centered to the subjects shoulder and positioned at a virtual wall at 95% of arm length. Reaching movements started from random starting points (SPs) evenly distributed within $\pm 45°$ around the target at distances of 15% (three SPs), 37.5% (five SPs), and 60% (seven SPs) of arm length. Subjects were to position the cursor at a given SP and move anytime following a ready signal. Movement duration, from self-initiated reach onset to reaching the virtual wall, was calculated for each reach and subjects were instructed to hit the target as many times as possible in a total movement time of 100 s. Each target hit was rewarded by 0.025 euros. Accumulated reward, remaining time, target, SP, and visual feedback of the hand cursor were shown in real time. Overall reach accuracy was comparable across all SPs. Kinematic data were analysed for reaches starting from $+45°$ (rightward diagonal reach), $-45°$ (leftward diagonal) and $0°$ (straight) at the three SPs distances. Trajectory length and movement duration were calculated for 307 accurate target hits and averaged over subjects and SPs. Following a paired t-test $+45°$ and $-45°$ SP data were collapsed. Statistics were conducted at $\alpha = 0.05$.

Trajectories differed significantly from the Euclidean distances between the SP and the target for all $45°$ SPs ($0.9 \quad 1.3cm$) longer, paired t-test all $p < 0.02$) and for $0°$ SP at the shortest distance ($2mm$, paired t-test $p = 0.02$). Angle influenced both trajectory prolongation and duration, but distance between the target and the SP affected only movement duration ($p < 0.02$ for all, repeated measures ANOVA).

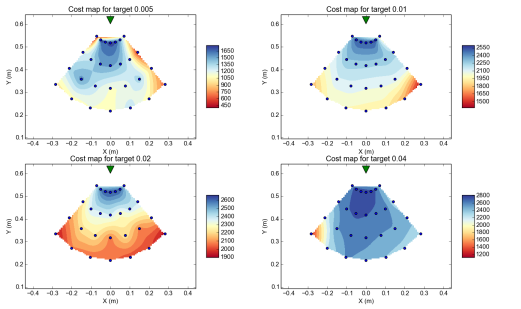
Subjects reached the target with equal success from all SPs, but their movement trajectories were curved when reaching at $45°$, unlike mostly straight movements at $0°$. Such behaviour might reflect task generalization to reaching forward in the sagittal plane[50], possibly due to complexities caused by different SPs. Computational modelling of this behaviour, taking into account the underlying muscle activity, is performed by UPMC.

To this end, UPMC has proposed a computational model of reaching movements designed to explain the phenomena studied experimentally by JSI. The model unifies a cost-benefit trade-off [51] and a speed-accuracy trade-off [52] to explain movement properties related to time. Precision constraints are incorporated through the derivation of an optimization criterion that considers probabilistic reaching of a rewarding target that may be missed if the motion is too fast.

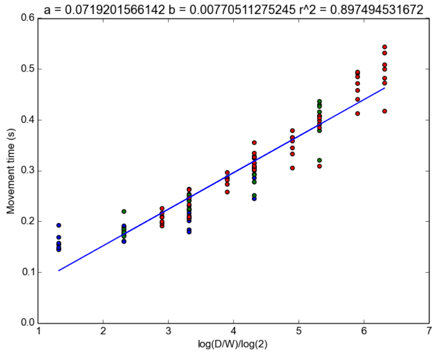
The model has been coded in python. The movement controller is implemented as an artificial neural network to which supervised learning (aka regression) is applied to obtain a initial good enough behaviour. Once this controller is initialized, an optimization process is applied to 4 instances of the weights of the artificial neural network to obtain 4 different controllers whose behaviour is optimized to 4 different target sizes. We then check the properties of the obtained controllers with respect to what is expected from the experimental movements recorded at JSI. The results are depicted in Figure 23a to 23d.



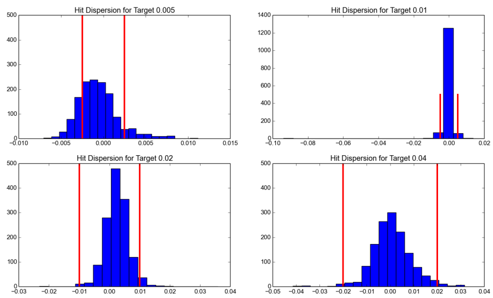
(a) Reaching trajectories obtained with the four optimized controllers.



(b) Cost of movement from any starting point to reach the 4 different targets.



(c) Reproduction of Fitts' law obtained from the data above.



(d) Hit dispersion obtained with the four optimized controllers.

Figure 23

As one can see, the model consistently obtains Fitts' law (Figure 23c), with a very good r^2 factor of 0.90 (to be compared to the 0.92 obtained by JSI on human movements). The maps showing the cost of movement as a function of the starting point (Figure 23b) are also consistent with the ones of JSI, as is also the case with the hit point dispersion depending on the size of the target (Figure 23d). Globally, the modelled arm controller is able to slow down to improve accuracy of reaching when the targets are smaller, which was the main expected outcome of the model. The velocity profiles of the corresponding movements (not shown) are also satisfactory. However, the obtained reaching trajectories (Figure 23a) are more curved than those recorded at JSI. We are currently investigating the potential impact of the optimization process on this phenomenon and envisioning using new deep reinforcement learning tools [53] instead of stochastic optimization [54] to accelerate the optimization process.

Resources

WP3 person months	IIT	TUD	UPMC	UB	JSI	INRIA
Year 1	9.90	4.60	15.15	-	-	-
Year 2	-	10.5	14.67	1.85	1.00	4.14
Year 3	-	9.65	8.79	1.63	2.00	4.03
Partial	9.90	24.75	38.61	3.48	3.00	8.17
Overall	9.00	24.00	43.5	10.00	4.00	10.50

In order to best use the whole-body controllers developed within the framework of WP3, TUD hired a student for setting up the iCub hardware and simulation environment.

Deviations from workplan Due to the resignation of Mingxing Liu from her postdoc position in November 2015, UPMC could not dedicate as many person months as expected on WP3, in particular T3.4. To compensate for that, UPMC dedicated internal resources on T3.4 (PhD work of Ryan Lober). Also, the recruitment of Jorhabib Eljaik as a postdoc, starting in May 2016, will permit to execute the corresponding work on Model Predictive Control for supportive hand reactive planning over the fourth year.

3.3.2.4 Work package 4 progress

Improved Models from Real-Time Regression with Latent Contact Type Inference (T4.1) Within T4.1 IIT developed in the first and the second year of the project a theoretical framework for estimating whole-body dynamics from distributed multimodal sensors [55]. Considered sensors include joint encoders, gyroscopes, accelerometers and force/torque sensors. Estimated quantities are position, velocity, acceleration and (internal and external) wrenches on all the rigid bodies composing the robot articulated chain. In the third year of the project, IIT investigated the integration of this estimation techniques with the classical identification techniques for inertial parameters that were implementer in software packages as part of T1.4 .

In [55], the estimation of dynamics quantities was performed by using the uncertancy of each sensor was learned using real data. In particular the Expectation-Maximization algorithm was used to estimate the covariance matrix of each sensor. IIT focused on extending this EM algorithm to also learn the mass, center of mass and inertia matrix of each link of the robot. This extension was validated in simulation and submitted in [56].

Whole-body human dynamics estimation for compliant human-robot interaction Although not directly scheduled as a task for the third year, IIT is currently involved in the development of a human wearable prototype of sensors suit which has strong connections with WP2 and will be a fundamental technology for the last year of the project and the associated validation scenario. The proposed suit tracks human motions and records the forces that he is exchanging with the robot giving real-time whole-body estimations of the human dynamics. This novel technology will endow robots with the ability to understand and control physical collaboration in human-robot physical interaction.

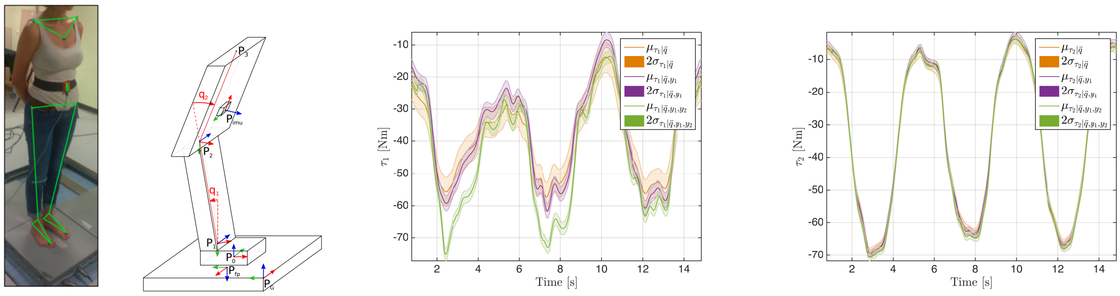


Figure 24: Perliminary experiment for real-time estimating human whole-body dynamics with distributed accelerometers and force/torque sensors. The technology is the same originally devloped for the iCub, modified to becomes a wearable technology. At present a single IMU and force-plate are used. In this preliminary experiment only ankle and hip torques were estimated.

Introduction and problem statement: Human whole-body motion tracking is nowadays a well-established tool in the analysis of human movements. Well known examples include: a wearable marker-less technology suitable for outdoor motion capturing produced by Xsens [57], a state-of-the-art marker-based technology for in lab applications produced by Vicon, and Microsoft's Kinect depth camera system which allows marker-less low-cost whole-body motion tracking for indoor applications [58]. Although existing technologies provide a high level of accuracy in computing motion quantities, they have several limitations in measuring kinetic quantities in real-time (kinetics considers forces that cause movements). A key problem lies in the fact that motion capture methods typically employ only kinematic measurement modalities (position, velocities and accelerations) [59] and does not include information on the kinetics of human movements. Whole-body force tracking is not a new challenge for the scientific community but the topic has been seldom explored *in situ* due to the computational difficulties of the analysis and even more rarely analyzed in a real-time modality. Although several recent studies are going in this direction, it is limited to prototypical and non-wearable technologies.

Methodology: Our methodology attempts to estimate dynamics quantities by exploiting the fusion of the sensor information on a probabilistic Gaussian framework in presence of redundant (and noisy) measurements [60]. The framework is based on the idea of building a joint probability for all the dynamic variables and measurements coming from multiple sensors and to compute the estimation as the conditioned probability of the variables themselves given the measurements. Preliminary results show that the variance associated to each estimated variable decreases as the number of considered measurements (sensors) increases.

Inferring the Operational Space and Appropriate Controls with Multiple Contacts (T4.2) (TUD: 6PM) During year two, TUD and JSI investigated the effect of supportive contacts on postural control. First results were presented during the second year review meeting (Task T2.4 on Human contact choice and learning through physical interaction). During year three, we collected a large dataset of more than 9.000 reaching movements in 20 subjects. To analyze the data TUD developed a probabilistic model which extends classical statistical tests (ANOVA test of contact locations and target locations, movement onsets, etc.). The probabilistic model allows for detailed investigations of movement kinematics in

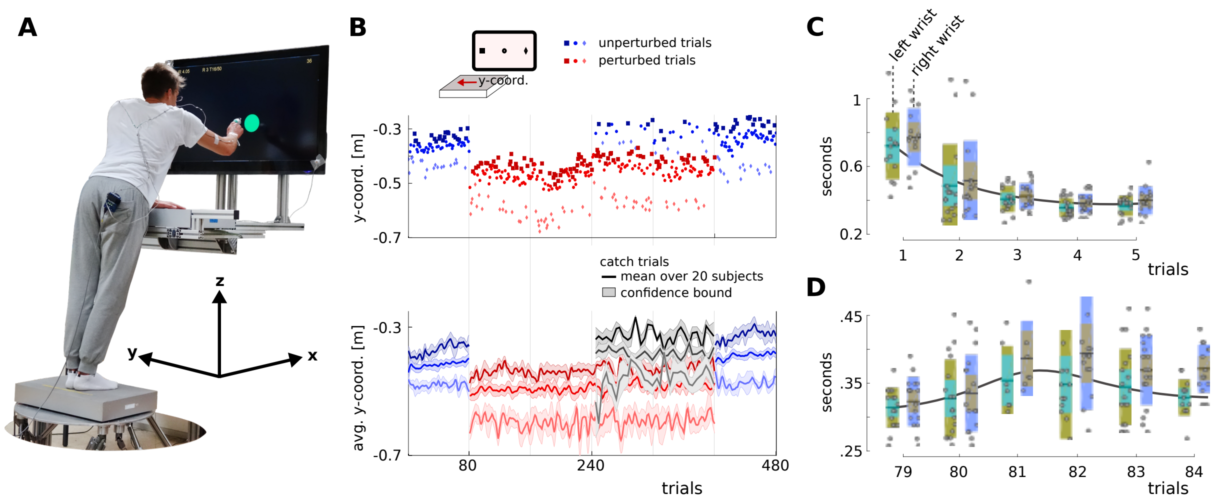


Figure 25: **Experiment, target dependent contacts and synchronized arm motions.** **A)** Experimental setting. **B)** The top row shows contact locations for a single representative subject and the bottom row shows the mean and the confidence bound over all 20 participants. The first 80 trials and the last 80 trials are unperturbed sessions. Catch trials were initiated during trials 240 to 400 and are denoted by the black lines in **B**. **C)** Illustration of the movement onsets of the wrists for the first five trials. **D)** Movement onsets for the first six trials transitioning to the perturbed session.

a spaciotemporal domain and extends classical techniques that rely on scalar descriptors of the complex motion patterns. In whole body adaptation experiments, shown in Figure 25, TUD and JSI found strong correlations between both arms and the trunk. These correlations were used to predict the reaching motion from early phase observations of the supportive contact motion. The results suggest that postural control predicts and precedes goal-directed movements, which has the potential to impact pre-tests of central nervous system disorders like dementia, Alzheimer's or Parkinson's disease that are less prone to factors like stress, sleep deprivation and age compared to the classical cognitive tests. A pre-print of a paper that was submitted for review to Scientific Reports is given in Deliverable D2.2.

In ongoing work, TUD and JSI investigate how such probabilistic models can predict when and how to make supportive contacts in robot reaching tasks. Our goal is to reproduce the correlated reaching and supportive contact motions in the iCub robot. In addition to the target dependent contact locations, a module that predicts when to initiate a supportive contact will be developed. This model will make use of the estimated center of pressure using the two force/torque sensors in the ankles.

In another approach, TUD investigated computational models of operational space control in rodents using spiking neural networks. While this study is more of a fundamental type and does not directly provide concrete algorithms for humanoid robot control, it has interesting potentials for the challenging tasks in CoDyCo. Concretely, in spiking neural networks arbitrary-shaped obstacles can be modeled, non-linearities in the transition model due to contacts can be learned and movement plans can computed much faster then real-time through exploiting local-only dependencies. These advantages were evaluated in target-reaching task in a Kuka robot arm. For that TUD developed learning algorithms grounded in the theory of probabilistic

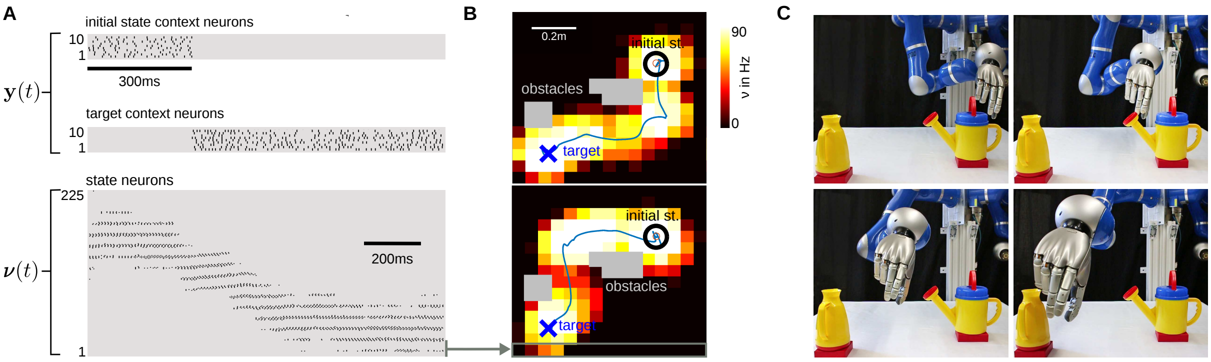


Figure 26: **Planning with multiple constraints on a real robot. A)** Generated spike train (top: context neurons, bottom: state neurons) after contrastive divergence learning of the transition model. **B)** Two sampled movement plans solving the obstacle avoidance task. **C)** Snapshots of the executed movement on the real robot.

inference to train the recurrent spiking neural network from human demonstrations. The training data was collected in kinesthetic teaching. After the training, the network model was used to plan goal-directed task space trajectories that avoid obstacles in the three-dimensional space. Two example movements and the corresponding neural activity are illustrated in Figure 26. For details on the approach we refer to Deliverable D4.1. A manuscript on this work was accepted for publication in Scientific Reports [5] (impact factor 5.578 in 2014).

In a student's master thesis, TUD extended the model to jointly model configuration and task spaces. This extension is based on factorized population codes and allows for applications to high-dimensional robot systems. In ongoing work, TUD will test the learning algorithms of the spiking network in the iCub robot.

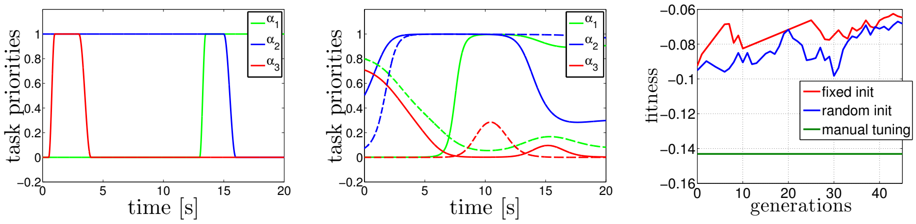
Learning the Prioritization of Tasks (T4.4) (TUD: 6PM, UPMC: 0.74) During the third year, TUD continued its research on learning controllers for physical interaction. We presented a novel approach at an international robotics conference [6]. The approach learns and generates movements for physical interaction that are trained with imitation learning from a small set of demonstrated trajectories. Learning such a model is a non-trivial task and therefore we introduced the *model-free* Probabilistic Movement Primitives (ProMPs). Here, we learn jointly the movement and the necessary actions from a few demonstrations. We derived a variable stiffness controller analytically and we extended the ProMPs to include force and torque signals, necessary for physical interaction in the CoDyCo scenarios.

Based on these results we also focused on developing a novel approach for task prioritization during year three. Our approach follows the concept of "soft" priorities, where a task which is lower in the task-hierarchy can controllably interfere with a higher-priority task. This concept is applicable to a wide-set of problems including balancing and reaching in humanoids with physical contacts with the environment. In our approach we dynamically change the priority of each task in time and, thus, adapt the behavior of the robot dynamically. The approach utilizes imitation learning to obtain the variance of each task movement which is then used as the relative priority of the task. An important contribution of our approach shows how we can utilize probabilistic methods to analytically derive the tasks priorities from the imitation learning. We relate our approach to other state-of-the-art movement prioritization approaches [61, 7] and we show how these approaches can be derived under our framework. We provide an alternative point of view on movement prioritization that is derived from first-order principles. We demonstrated that our approach achieves improved performance and that is numerically stable, avoiding singularities. A paper on this approach was submitted to a robotics conference.

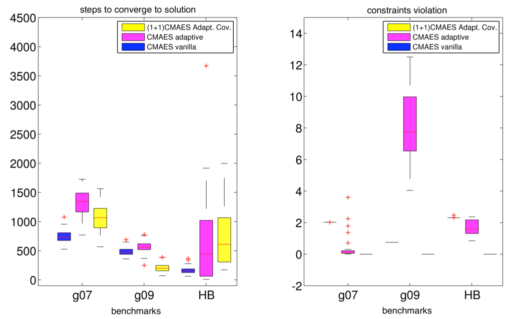
UPMC developed whole-body controllers allow multiple concurrent tasks to be executed on redundant robots, and such combinations often engender unforeseeable incompatibilities between the tasks due to conflicting task objectives and the robot's constraints. The result is typically a failure of one or more tasks to be properly carried out. In [62], UPMC introduced a measure of task compatibility, or compatibility cost. By optimizing parametric task representations, UPMC was able to minimize said cost and render the tasks compatible, albeit slowly. In [7], UPMC looked at how task priorities could be automatically modulated by the variance associated with each task. This provided a reactive way to handle many common incompatibility scenarios. Currently, lately UPMC has been working on more computationally efficient task compatibility optimization schemes which combine the previous two works.

INRIA, in collaboration with TUD, has been working on the problem of automatically optimizing the soft task priorities for multi-task controllers. The goal of this work is to facilitate the automatic tuning of the task weights and task transitions when multiple elementary tasks are used to realize a more complex "global" task or movement. When the number of tasks increases, for example in whole-body control of humanoid robots, it is generally difficult to define suitable task activations: the task weights/priorities and their transitions are manually tuned by expert users or defined before-hand. In [46], INRIA proposed a framework to automatically optimise the soft task priorities by means of a stochastic optimization algorithm. In the framework, the temporal profiles of the task weights, approximated by a mixture of Gaussian, can be learned by optimizing a given fitness function used to evaluate the performance of the candidate task priorities. Optimization was done by the state-of-the-art CMA-ES algorithm. The method has been evaluated on the redundant manipulator Jaco and a simulated KUKA LWR, showing that it improves the fitness of the gloabl movement and the smoothness of the joint trajectories (see Figure 27a). The work has been also presented in [63]. Currently, INRIA is working towards two main improvements on this framework: 1) to scale-up the framework to the iCub, to study its performance in handling several DOF and several tasks; 2) to include the constraints evaluation in the optimization process, such that the optimization process always generates solutions that cannot violate constraints; this is done by guiding the exploration with both the fitness and the constraints violations functions: preliminary results indicate that a (1+1)-CMA-ES seems to be the best candidate algorithm to address this issue (see Figure 27b). A paper is in preparation.

Resources



(a) Manually tuned vs optimized task weights (solid line: fixed init, dashed line: random init). The fitness for the optimizes weights is smaller (better). More in [46].



(b) Comparison of three variants of constrained CMA-ES on benchmarks. (1+1)-CMA-ES never violates the constraints, despite requiring more time to converge to the optimal solution.

Figure 27

WP4 person months	**IIT**	**TUD**	**UPMC**	**UB**	**JSI**	**INRIA**
Year 1	-	8.00	2.22	-	-	-
Year 2	6.04	21.70	1.69	2.15	3.00	2.01
Year 3	9.79	12.00	0.74	1.68	3.00	3.30
Partial	15.83	41.70	4.65	3.83	6.00	5.31
Overall	30.00	38.00	9.00	12.00	10.00	9.00

Deviations from workplan TUD substantially underestimated the number of required PMs for the project and already consumed all assigned PMs during the first three years (79.9 PMs were used out of 76 PMs). It appears that 6.75 PMs are needed to complete Task 4.2, Task 4.3 and Task 4.4 in year 4. Due to the temporary problems of hiring a senior researcher in year one, two junior researcher had to fill this gap. Thus, there still exists sufficient budget for 4.75 PMs while TUD aims to contribute 2 PMs from its own endowed funding. IIT is slowly committing more resources to this work package and the hiring of Francesco Romano as a postDoc will allow to provide the planned contribution. In conclusion, this will result in no significant deviation from planned activities.

3.3.2.5 Work package 5 progress As previously mentioned, the activities for the Work-Package 5 have focused on the implementation of the third-year validation scenario.

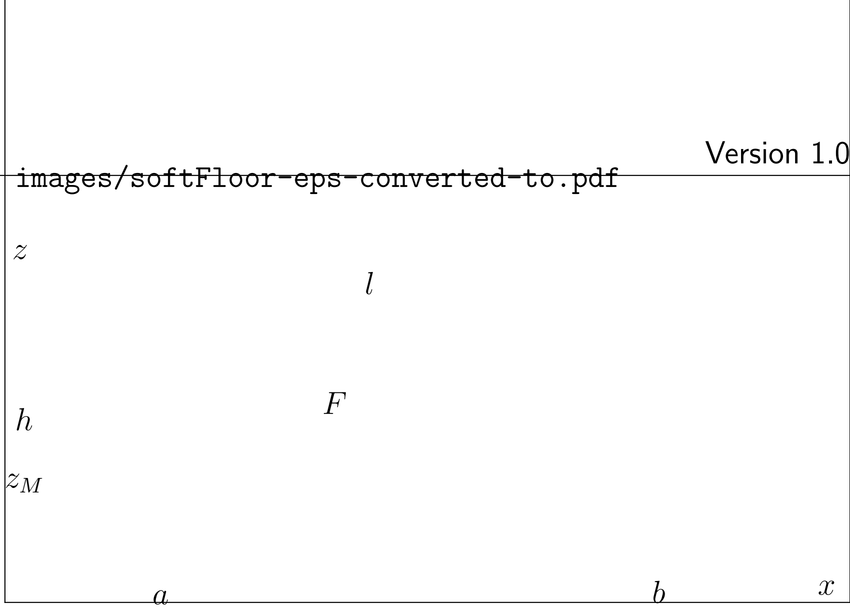


Figure 28: A compliant carpet subject to a uniform force distribution

Let us recall that this scenario aims at verifying the control performances in the case the humanoid robot iCub must balance by means of compliant or dynamical contacts (see [4] `https://github.com/robotology-playground/codyco-deliverables/blob/master/D5.3/pdf/D5.3.pdf`).

In particular, the validation scenario consists in two demonstrations carried out with the humanoid robot iCub: balancing on a soft carpet and balancing on a seesaw. In both cases, the control objective is the regulation of the robot momentum. The main idea to control the robot momentum is that its rate-of-change equals the summation of the external wrenches acting on the system. So, controlling the external wrenches allows us to control the rate-of-change of the robot momentum and, as a consequence, the momentum itself.

Demonstration 1: iCub balancing on a compliant carpet One of the main difficulties when dealing with compliant contacts comes from the fact that the external wrenches acting on the robot may not be instantaneously related to the robots torques, i.e. the input to the system. As a consequence, the input does not influence instantaneously the rate-of-change of the robot's momentum, and this complexifies the robot's control. This complexity arises, for instance, when a humanoid is standing on two springs that exert forces on the robots feet depending on the relative compression only. There may be some particular compliant terrains, however, that exert forces and torques not only depending on the relative compression, but also on the robots joint torques. In these cases, the soft terrain is subject to some rigid constraints that may allow the control of the robots momentum through the external forces, which thus depend on the joint torques. This is the case of a thin, highly damped carpet, which can be modeled, in the first approximation, as a continuum of vertical springs (see Figure 28). Each of these springs is assumed to compress vertically only, and the other degrees of freedom are rigidly constrained, thus creating the aforementioned relation between external forces and joint torques. This relation allows us to control the robot's momentum through the joint torques when the robot stands on a compliant carpet.

Demonstration 2: iCub balancing on a seesaw When the robot stands on a seesaw (see Figure 29), the contacts between its feet and the environment (i.e. the seesaw) are subject to a non-trivial dynamics. The difficulties when controlling the robot's momentum in this case are a higher than those when the robot stands on the compliant carpet. In fact, in

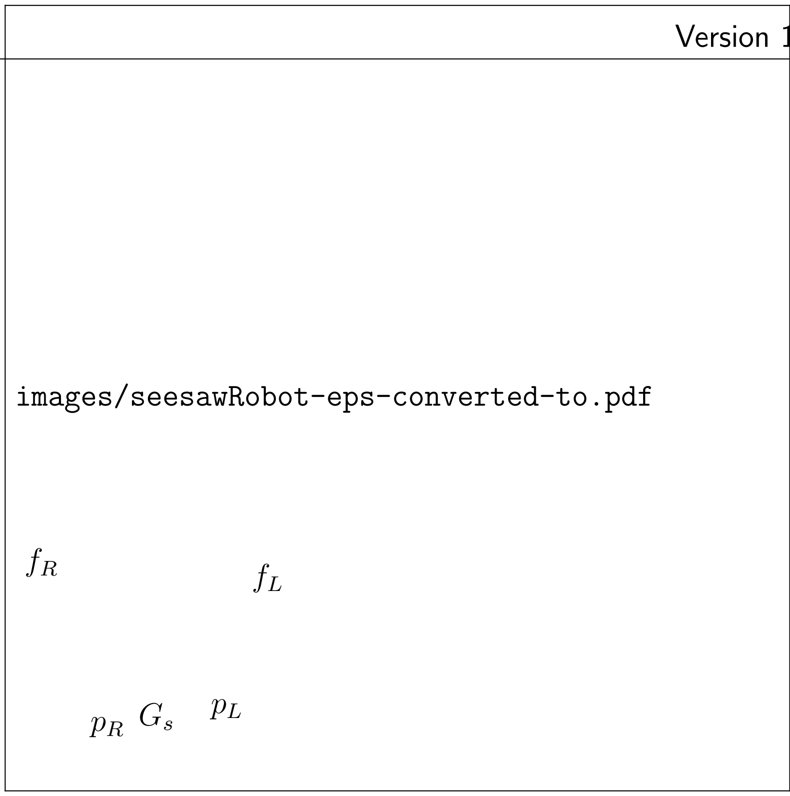


Figure 29: The robot balancing on the semi-cylindrical seesaw

addition to the fact that the rate-of-change of the momentum may not be instantaneously affected by the system's input (torques), we have the dynamics of the seesaw to take into account. The constraints to take into account are thus: the robot's feet must be attached to the seesaw, the seesaw can roll on the floor. By combining these constraints with the robot and seesaw dynamics, it is possible to calculate the contact wrenches (between the robot and the seesaw) so as to control the robot's momentum.

Software The controllers for both demonstrations have been developed in the MATLAB-SIMULINK environment thanks to the WB-Toolbox library (`https://github.com/robotology-playground/WBI-Toolbox`), a wrapper which allows us to use the high-level MATHWORKS tools. In particular, the controller for balancing on a compliant terrain is available at `https://github.com/robotology-playground/WBI-Toolbox-controllers/tree/master/controllers/torqueBalancing`, while that for balancing on a seesaw at `https://github.com/robotology-playground/WBI-Toolbox-controllers/tree/master/controllers/torqueBalancingOnSeesaw`.

Resources Resources were used with no difference with respect to what planned.

WP5 person months	IIT	TUD	UPMC	UB	JSI	INRIA
Year 1	2.00	-	0.31	-	-	-
Year 2	12.00	0.85	0.05	-	-	-
Year 3	13.06	2.00	0.14	1.44	-	0.52
Partial	27.06	2.85	0.50	1.44	-	0.52
Overall	48.00	5.00	2.50	-	-	1.50

Deviations from workplan No significant deviation from the workplan. The validation scenarios will include all the theoretical and technological challenges detailed in the original plan.

3.3.2.6 Work package 6 progress Activities within work package 6 achieved the expected results both in terms of administrative activities and management activities. As a major achievement, the management successfully concluded a third amendment to include INRIA as a partner. The inclusion was motivated by the the new position of Dr. Serena Ivaldi, currently researcher at INRIA, Nancy.

Administrative coordination (T6.1) Administration was successfully coordinated by IIT, with significant contribution from Chiara Andreoli (iCub Facility), Giulia Campodonico (project offices) and Maria Carmela Fierro (Robotics, Brain and Cognitive Science Department). The major activity concerned the amendment that the CoDyCo consortium asked the main reason being the fact that Serena Ivaldi, initially hired by UPMC and successively moved to TUD, was recently hired by INRIA as researcher. Part of the administrative coordination activities were also conducted during the mid-year meeting: Birmingham, Tuesday 15th December 2015. Details on the meetings can be found in the CoDyCo website (`http://www.codyco.eu`).

Software repository implementation (T6.2) The github software repository was several times restructured `https://github.com/robotology/codyco` and the contribution from the different developers can be directly checked in the website.

Resources Resources were used as follows.

WP6 person months	IIT	TUD	UPMC	UB	JSI	INRIA
Year 1	1.46	-	0.25	-	-	-
Year 2	1.50	-	0.31	-	-	-
Year 3	1.51	1.00	0.19	-	0.44	-
Partial	4.47	1.00	0.75	-	0.44	-
Overall	5.00	1.00	1.00	0.60	1.00	-

Deviations from workplan No significant deviations.

3.3.2.7 Work package 7 progress Dissemination and exploitation activities included the participation to international events addressed to both commercial and academic institutions.

Dissemination activities towards academia, industry, and other users (T7.1) Dissemination activities were conducted thorough international publications, organisation of international events, talks at international conferences, press interviews and iCub expositions at international events. Here is the overall contribution subdivided by partner:

- IIT: 4 invited visiting periods, 4 international events participation, 12 publications (4 journal articles, 8 international conferences), several media coverage events.
- TUD: 9 invited talks, 1 organised international events, 12 publications (2 journal articles, 10 international conferences), 3 media coverage events, 3 M.Sc. theses and one Ph.D. thesis.
- UPMC: 7 invited talks, 4 other events, 5 paper presentations at international Conferences, 1 international journal, 5 international conferences.
- UB:
- JSI: 2 invited talks, 1 editorial for journal special issue, 3 publications (2 journal, 1 internal conferences), 0 media coverage events.
- INRIA: 11 publications: 4 journals, 4 conference papers, 3 workshop papers, 2 international workshops: ICRA 2015 and BMVA 2015, 1 special issue organization in Autonomous Robots, dissemination of activies in several media.

Live demonstration of the iCub have been performed at several international and national events. Some of these events were sponsored by CoDyCo and the following is a non exhaustive list:

1. Live video shooting at "Italia's got talent", italian national television show. Shooting: December 1st-3rd 2015. Location: Catanzaro, Italy. The iCub performed the CoDyCo demo based on whole-body torque controlled motions with switching motions.
2. Live demonstrations at the event: "Italian Manufacturing Forum", UIC Gleacher Center, Chicago, IL, March 30th, 2016. The iCub was shipped to Chicago to perform several iCub related demonstrations (e.g. iCub standing, iCub performing whole-body equilibrium tasks) at the Italian Manufacturing Forum.

Among the invitations as a speaker at international events it is worth citing the following:

1. Francesco Nori invited talk at the dissemination event Creative mornings. Talk: Interacting with Humans with iCub-humanoid. Dates: Location: May 22nd 2015. Milano, Italy.
2. Francesco Nori invited talk at Convegno NanoItaly, Roma, 21-24 settembre 2015. Talk: Force and motion capture system based on distributed micro-accelerometers, gyros, force and tactile sensing. Date: 21 settembre 2015.

3. Talk by Elmar Rueckert, 02/2015 Probabilistic Inference and Modeling of Human Motor Skill Learning. Invited Talk. Workshop with Marc Toussaints group, Wolfram Burgards group and Oliver Brocks group, Manigod, France.

4. V. Padois. Robotique industrielle: volution, enjeux et perspectives, January 2016. Invited talk at CNER/SERECT.

5. Ivaldi, S. (12/2015) Human-robot interaction with iCub. Invited talk at University of Plymouth, by Samantha Adams and Angelo Cangelosi.

6. Babic, Jan. Human-in-the-loop control of robots for industrial assembly tasks : invited talk, Omron Keihanna Technology Innovation Center, 7th September 2015, Kyoto, Japan.

Among the organised international events here is a non exhaustive list of the most relevant events:

1. The iCub Summer School, "Veni Vidi Vici". The iCub Summer School July 22-31, 2015. The school focuses on humanoid robotics and will host at least two iCub and a COMAN robot.

2. ICRA 2015 Workshop ICRA 2015 Workshop "Get in touch! Tactile & force sensing for autonomous, compliant, intelligent robots", May 30th 2015, Seattle (USA), organized by S. Ivaldi, L. Jamone and B. Siciliano (`http://www.ausy.tu-darmstadt.de/Workshops/ICRA2015TactileForce`). The workshop had 147 registered participants.

3. In July, during the RSS conference in Rome, a full day workshop titled "Towards a Unifying Framework for Whole-body and Manipulation Control" has been organised. Topics covered the following areas: contacts planning and control; whole-body task control; compliant whole-body movements; dynamics in humanoid robots; machine learning and optimization methods for contact planning and control.

Resources Resources were used as follows.

WP7 person months	IIT	TUD	UPMC	UB	JSI	INRIA
Year 1	1.00	-	0.40	-	-	-
Year 2	-	-	0.13	-	-	0.91
Year 3	1.00	-	0.11	-	-	-
Partial	2.00	-	0.64	-	-	0.91
Overall	3.00	1.00	1.00	1.00	1.00	1.00

Deviations from workplan No significant deviations.

3.4 Deliverables and milestones tables

3.4.1 Deliverables (excluding the periodic and final reports)

Del. no.	Deliverable name	WP	Type[1]	Dissemination level[2]	Delivery date	Task involved	Responsible	Person Month
D1.3	Software for dealing with compliant contacts.	1	SW	PU	M36	T1.4 T4.1 T1.3 T3.3 T3.4	UB	16
D2.2	Models of human whole body motions in contact with rigid and compliant support surfaces.	2	R	PU	M36	T2.2 T2.3	JSI	66
D3.2	Local solver in compliant-world cases.	3	R	PU	M36	T3.1 T3.2 T3.3	UPMC	26
D4.1	Learning approaches for operational space control with contacts.	4	R	PU	M36	T4.1 T4.2	TUD	50
D5.3	Validation scenario 3: balancing on compliant environmental contacts.	5	R	PU	M36	T5.3	IIT	15

1 Nature of the deliverable:
R = Report, **P** = Prototype, **D** = Demonstrator, **SW** = Software, **O** = Other

2 Dissemination level:
PU = Public
PP = Restricted to other programme participants (including the Commission Services).
RE = Restricted to a group specified by the consortium (including the Commission Services).
CO = Confidential, only for members of the consortium (including the Commission Services).

3.4.2 Milestones

Milestone number	Milestone name	Work package(s) involved	Expected date [1]	Leader	Means of verification
MS.3	Validation scenario 3: balancing on compliant environmental contacts	MS.2 T1.4 T2.3 T3.4 T4.1 T5.3	M36	IIT	- The iCub successfully and robustly stands on multiple compliant contacts

[1] Measured in months from the project start date (month 1).

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A List of dissemination events

A.1 IIT contributions to dissemination

4 invited visiting periods, 4 international events participation, 12 publications (4 journal articles, 8 international conferences), several media coverage events.

Figure 30: The iCub CoDyCo demonstration at the national television show Italia's got talent.

A.1.1 Invited talks

1. Event: Francesco Nori invited researcher at Tokyo University (Japan), Laboratory for Intelligent Systems and Informatics, Department of Mechano-Informatics, School of Information Science and Technology. Period: from October 1, 2015 to October 31, 2015.

2. Event: Francesco Nori invited researcher at AIST (Japan), CNRS-AIST Joint Robotics Laboratory UMI3218/RL (JRL) situated at the Intelligent Systems Research Institute (IS), National Institute of Advance Industrial Science and Technology (AIST). Period: from November 15, 2015 to December 6, 2015.

3. Event: Francesco Nori invited researcher at Universite Paris Sud (France). University Paris Sud 11, Paris. CIAMS laboratory in the Motor Control and perception team, University Paris-Sud 11, Paris, France. Inviting professors: Prof. Bastien Berret, University Paris-Sud 11 and Prof. Frédéric Jean, ENSTA Paris-Tech, Unité de Mathématiques Appliquées. Period: from June 1, 2015 to June 30, 2015.

4. Event: Francesco Nori invited researcher at INRIA, Nancy (France). Serena Ivaldi invited Francesco Nori from January 25th to Febraury 19th to spend a visiting periodo at team Larsen, INRIA. Inviting researcher: Serena Ivaldi. Period: from January 25th to Febraury 19th, 2016. During this visiting period Francesco and Serena planned the activities for the fourth year demonstration.

A.1.2 International events participation

1. The iCub Summer School, "Veni Vidi Vici", serves to consolidate and disseminate skills in software engineering for humanoid robots. Our goal is to foster collaboration on robot software across the boundaries and lifetimes of specific platforms and projects. The school focuses on humanoid robotics and will host at least two iCub and a COMAN robot. Students will receive an initial training on the software infrastructure (middleware and tools) and will be required to work on a project of their choice. All participants are

Figure 31: Top left: the iCub Veni-Vidi-Vici summer school. Top right: the iCub at the IROS 2015 event organised by the robotics unit at the European Commission. Bottom left: iCub with the piano player, Giovanni Allevi. Bottom right: icub with Matteo Renzi at the "Italian Manufacturing Forum".

expected to be competent C/C++ programmers with an interest in working with others (and an agenda of their own). Info: `http://wiki.icub.org/wiki/VVV15`

2. During the IROS 2015 International Conference at Hamburg, different versions of iCub (the Genova Black, and the Heidelberg version) were shown in an exhibition. For three days, iCub interact with visiting people performing different demos, such as torque balancing and the red ball demo. Photo by Fabian Bimmer/Reuters)

3. In July, during the RSS conference in Rome, a full day workshop titled "Towards a Unifying Framework for Whole-body and Manipulation Control" has been organised. Topics covered the following areas: contacts planning and control; whole-body task control; compliant whole-body movements; dynamics in humanoid robots; machine learning and optimization methods for contact planning and control.

4. Live demonstrations at the event: "Italian Manufacturing Forum", UIC Gleacher Center, Chicago, IL, March 30th, 2016. The iCub was shipped to Chicago to perform several iCub related demonstrations (e.g. iCub standing, iCub performing whole-body equilibrium tasks) at the Italian Manufacturing Forum.

A.1.3 Other events

1. iCub has been a special guest in Balları́ó, an italian political show on the public television network. The video of the event is available here: `https://youtu.be/DE3VynOr6HE`.

2. In May, Francesco Nori was an invited speaker at the Creative Mornings event. The talk gave historical and philosophical motivations that guided recent research activities towards the problem of studying how humans interact with the environment and among themselves. The iCub was also presented, as an open-source platform capable of advancing the state-of-the-art in various directions, e.g. decisional autonomy, dependability/adaptability, perception and, in a single all-embracing word, cognitive abilities.

3. From 22nd of October to 1st of November 2015, the iCub will be showed at the "Festival della Scienza". Festival della Scienza, now at its 13th edition, is a publicly opened event which focus on science. During this festival, temporary laboratories and exhibition booths are prepared where researchers and scientists can show and explain to people their work. Presentations are targeted to different audiences, from children to university students to adults. This year festival theme is "Equilibrium", and iCub will perform daily showing balancing demos.

4. Live video shooting at "Italia's got talent", italian national television show. Shooting: December 1st-3rd 2015. Location: Catanzaro, Italy. The iCub performed the CoDyCo demo based on whole-body torque controlled motions with switching motions.

A.1.4 Talks at international conferences

1. Event: invited talk at the dissemination event Creative mornings. Talk: Interacting with Humans with iCub-humanoid. Dates: Location: May 22nd 2015. Milano, Italy.

2. Event: Convegno NanoItaly, Roma, 21-24 settembre 2015. Talk: Force and motion capture system based on distributed micro-accelerometers, gyros, force and tactile sensing. Date: 21 settembre 2015.

3. Event: International Conference on Humanoid Robotics, 02-06 November 2015. Workshop on Benchmarking bipedal functions of humanoids robots: towards a unified framework. Talk: wholeBodyInterface: a software abstraction layer for benchmarking whole-body motion control. Date: November 3rd 2015.

4. Event: International Conference on Humanoid Robotics, 02-06 November 2015. Workshop on Reusable and Open-Source Modules for Humanoid Robots. Talk: wholeBodyInterface: An Open- Source Software Abstraction Layer for Whole-Body Motion Control. Date: November 3rd 2015.

5. Event: International Conference on Humanoid Robotics, 02-06 November 2015. Workshop on Whole-Body Multi-Task Multi-Contact Humanoid Control. Talk: iCub whole-body control through force regulation on rigid non-coplanar contacts. Date: November 3rd 2015.

6. Invited external member and president at Ph.D. defense Universite d'Orleans (France). Ph.D. candidate: Adina Panachea. Date: December 10th, 2015.

A.1.5 Pubblications

1. Camoriano R., Traversaro S., Rosasco L., Metta G. & Nori F. 2016, Incremental Semi-parametric Inverse Dynamics Learning, IEEE International Conference on Robotics and Automation (ICRA), Stockholm, Sweden, May 16-21, 2016.

2. Del Prete A., Mansard N., Ramos O., Stasse O. & Nori F. 2015, Implementing Torque Control with High-Ratio Gear Boxes and without Joint-Torque Sensors, International Journal of Humanoid Robotics.

3. Del Prete A., Nori F., Metta G. & Natale L. 2015, Prioritized Motion-Force Control of Constrained Fully-Actuated Robots: Task Space Inverse Dynamics, Robotics and Autonomous Systems, vol. 63, Part 1, pp. 150157.

4. Eljaik J., Kuppuswamy N. & Nori F. 2015, Multimodal sensor fusion for foot state estimation in bipedal robots using the Extended Kalman Filter, IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Hamburg, Germany, October (29 September - 1 October, 2015).

5. Latella C., Kuppuswamy N. & Nori F. 2015, Force and motion capture system based on distributed micro-accelerometers, gyros, force and tactile sensing, 2nd International Electronic Conference on Sensors and Applications,.

6. Nori F., Kuppuswamy N. & Traversaro S. 2015, Simultaneous state and dynamics estimation in articulated structures, IEEE/RSJ International Conference on Intelligent Robots and Systems (2015), Hamburg, Germany, October (29 September - 1 October, 2015).

7. Nori F., Traversaro S., Eljaik J., Romano F., Del Prete A. & Pucci D. 2015, iCub whole-body control through force regulation on rigid non-coplanar contacts, Frontiers in Robotics and AI.

8. Paikan A., Traversaro S., Nori F. & Natale L. 2015, Generic Testing Framework for Test Driven Development of Robotic Systems, in Jan Hodicky (ed.),Modelling and Simulation for Autonomous Systems Workshop, Springer International Publishing pp.216-225, , Prague, Czech Republic, 2015.

9. Pucci D., Romano F. & Nori F. 2015, Collocated Adaptive Control of Underactuated Mechanical Systems, IEEE Transactions on Robotics.

10. Romano F., Del Prete A., Mansard N. & Nori F. 2015, Prioritized Optimal Control: a Hierarchical Differential Dynamic Programming approach, IEEE International Conference on Robotics And Automation, Seattle, Washington, USA.

11. Traversaro S., Del Prete A., Ivaldi S. & Nori F. 2015, Inertial parameters identification and joint torques estimation with proximal force/torque sensing, IEEE International Conference on Robotics and Automation, Seattle, USA, May 26th - 30th, 2015.

12. Traversaro S., Pucci D. & Nori F. 2015, In Situ Calibration of Six-Axis Force-Torque Sensors using Accelerometer Measurements, IEEE International Conference on Robotics and Automation, pp.6, Seattle, USA, May 26th - 30th, 2015.

A.1.6 Media coverage

- https://youtu.be/DE3VynOr6HE
- https://youtu.be/mLqEkGwGxm0
- https://youtu.be/RBP4BvW4RBs
- https://youtu.be/RRg1yV_qKvY
- https://www.facebook.com/IITalk/videos/10156433813675384/
- https://youtu.be/im5k85_6t6s

A.1.7 iCub at international events

- CISCO conference Milano 26/1/2015
- Geo & Geo Roma 25/2/2015
- ERF Vienna, workshop on humanoids in the laboratory (chimica, ecc.) 12/3/2015
- ITURO conference Istanbul, keynote 11/4/2015
- CSIFT Shanghai, investors presentation 22-24/4/2015
- Bal Robotov, invited forum on robotics, Mosca 29/4/2015
- Robobusiness, invited, Milan 30/4/2015
- Boston Woodshole, summer school CBMM, Robotics Afternoon, 18-22/8/2015
- Sky International, TV, 25/8/2015
- Uno Mattina, Rai1, 1/9/2015
- Rai Petrolio, 10/9/2015
- Researchers night, invited, L'Aquila 26/9/2015
- Trieste Next Fest, invited, Trieste 27/9/2015
- IROS, Hamburg 28/9, 2/10/2015
- Italian Manufacturing Forum, Chicago, IL, 30/03/2016

A.2 TUD contributions to dissemination

9 invited talks, 1 organised international events, 12 publications (2 journal articles, 10 international conferences), 3 media coverage events, 3 M.Sc. theses and one Ph.D. thesis.

A.2.1 Invited talks

1. Talk by Roberto Calandra, 16 Oct 2015 University College London, London, UK, host: Guy Lever.
2. Talk by Roberto Calandra, 14 Oct 2015 University of Oxford, Oxford, UK, host: Michael Osborne, Machine Learning Research Group.
3. Talk by Roberto Calandra, 13 Oct 2015 Imperial College London, London, UK, host: Stefan Leutenegger, Dyson Robotics Lab.
4. Talk by Roberto Calandra, 03 Jun 2015 University of British Columbia, Vancouver, Canada, host: Mark Schmidt.
5. Talk by Roberto Calandra, 02 Jun 2015 University of Washington, Seattle, US, host: Dieter Fox, Robotics and State Estimation Lab.
6. Talk by Roberto Calandra, 01 Apr 2015 TU Freiburg, Freiburg, Germany, host: Frank Hutter.
7. Talk by Elmar Rueckert, 11/2015 Understanding Human Motor Control through Robotics Applications. Invited Talk in Prof. Constantin Rothkopfs seminar on research and applications of psychology in IT, Darmstadt, Germany.
8. Talk by Elmar Rueckert, 02/2015 Probabilistic Inference and Modeling of Human Motor Skill Learning. Invited Talk. Workshop with Marc Toussaints group, Wolfram Burgards group and Oliver Brocks group, Manigod, France.
9. Talk by Jan Peters, 06/2015 Universität Ulm, Host: F. Kargl, Ulm, Germany, July, 2015.

A.2.2 Pubblications

1. E Rueckert, D Kappel, D Tanneberg, D Pecevski and J Peters. Recurrent Spiking Networks Solve Planning Tasks. Scientific Reports, Nature Publishing Group, 2016.
2. R Calandra, A Seyfarth, J Peters and M P Deisenroth. Bayesian optimization for learning gaits under uncertainty. Annals of Mathematics and Artificial Intelligence, pages 119, 2015.
3. J Kohlschuetter, J Peters and E Rueckert. Learning Probabilistic Features from EMG Data for Predicting Knee Abnormalities. In Proceedings of the XIV Mediterranean Conference on Medical and Biological Engineering and Computing (MEDICON), 2016.

4. V Modugno, G Neumann, E Rueckert, G Oriolo, J Peters and S Ivaldi. Learning soft task priorities for control of redundant robots. In Proceedings of the International Conference on Robotics and Automation (ICRA), 2016.

5. R Calandra, S Ivaldi, M Deisenroth, E Rueckert and J Peters. Learning Inverse Dynamics Models with Contacts. In Proceedings of the International Conference on Robotics and Automation (ICRA). 2015.

6. R. Calandra, S. Ivaldi, Marc. P. Deisenroth, E. Rueckert, and J. Peters. Learning inverse dynamics models with contacts using tactile sensors. ICRA 2015 Workshop on Tactile & force sensing for autonomous, compliant, intelligent robots, 2015.

7. E Rueckert, J Mundo, A Paraschos, J Peters and G Neumann. Extracting Low-Dimensional Control Variables for Movement Primitives. In Proceedings of the International Conference on Robotics and Automation (ICRA). 2015.

8. S Traversaro, A Del Prete, S Ivaldi and F Nori. Avoiding to rely on Inertial Parameters in Estimating Joint Torques with proximal F/T sensing. In Proceedings of the International Conference on Robotics and Automation (ICRA). 2015.

9. A Paraschos, E Rueckert, J Peters and G Neumann. Model-free Probabilistic Movement Primitives for physical interaction. In Intelligent Robots and Systems (IROS), 2015 IEEE/RSJ International Conference on. 2015, 28602866.

10. E Rueckert, R Lioutikov, R Calandra, M Schmidt, P Beckerle and J Peters. Low-cost Sensor Glove with Force Feedback for Learning from Demonstrations using Probabilistic Trajectory Representations. In ICRA 2015 Workshop on Tactile and force sensing for autonomous compliant intelligent robots. 2015.

11. L Fritsche, F Unverzag, J Peters and R Calandra. First-person tele-operation of a humanoid robot. In Humanoid Robots (Humanoids), 2015 IEEE-RAS 15th International Conference on. 2015, 9971002.

12. R Calandra, S Ivaldi, M P Deisenroth and J Peters. Learning torque control in presence of contacts using tactile sensing from robot skin. In Humanoid Robots (Humanoids), 2015 IEEE-RAS 15th International Conference on. 2015, 690695.

A.2.3 Media coverage

1. 09/2015 Organized by Elmar Rueckert, Kinderuni Darmstadt. Interactive robot demonstrations of the Nao, the iCub and the Darias robots. Supported by Veronika Weber and Guilherme J. Maeda.

2. 04/2015 Interview of Jan Peters, Major German TV program, SAT1. Life demonstrations of teaching the iCub how to stack cup.

3. 03/2015 Organized by Elmar Rueckert, KID Science Radioclub. Lab tour and life demonstrations of the Oncilla, the iCub and the Darias robots. Supported by Veronika Weber, Guilherme J. Maeda, Rudolf Lioutikov and Roberto Calandra.

A.2.4 MSc. and Ph.D. theses

1. Stark S. MSc. thesis. Learning Probabilistic Feedforward and Feedback Policies for Generating Stable Walking Behaviors. 2016.

2. Kohlschuetter J. MSc. thesis. Learning Probabilistic Classifiers from Electromyography Data for Predicting Knee Abnormalities. 2016.

3. D Tanneberg. MSc. thesis. Spiking Neural Networks Solve Robot Planning Problems. 2016.

4. O Kroemer. Machine Learning for Robot Grasping and Manipulation. 2015.

A.2.5 Student research stays

1. E Rueckert, 2014. Jozef Stefan Institute, Slovenia, Department of Automation, Biocybernetics and Robotics, Prof. Dr. Jan Babic. Research internship on investigating the functional role of supportive contacts in human postural control.

A.2.6 Organised conference workshops

1. R. Calandra: Organizer of the Workshop on Bayesian Optimization (BayesOpt) at NIPS 2015. Web: http://bayesopt.github.io/

A.2.7 Invited speakers

1. W. Kellermann, Invited Speaker at TUDA, *Friedrich-Alexander Univerisität Erlangen-Nürnberg*, Erlangen, Germany, December, 2015.

2. D. Nikolic, Invited Speaker at TUDA, *Max-Planck Institut for Brain Research*, Frankfurt, Germany, January, 2016.

3. V. Lippi, Invited Speaker at TUDA, *Uniklinik Freiburg*, Freiburg, Germany, February, 2016.

4. F. Hutter, Invited Speaker at TUDA, *Universität Freiburg*, Freiburg, Germany, February, 2016.

A.2.8 Collaborations

1. UB and TUD, involved are M. Azad, M. Mistry, J. Peters, E. Rueckert. Title: *Uncertainty in contact*, first results on TUD's iCub. Paper submission planned for a robotics conference (HUMANOIDS, ICRA) in 2016.

2. TUD and JSI, involved are J. Babic, J. Camernik, J. Peters, E. Rueckert. Title: *Postural control predicts volitional motor control*, paper submitted for review at Scientific Reports, 01/2016.

A.3 UPMC contributions to dissemination

7 invited talks, 4 other events, 5 paper presentations at international Conferences, 1 international journal, 5 international conferences.

A.3.1 Invited talks

1. V. Padois. Robotique industrielle: volution, enjeux et perspectives, January 2016. Invited talk at CNER/SERECT.

2. N. Perrin. Quelles mathmatiques pour le contrle du mouvement humanode ?, January 2016. Invited Seminar at the Math-club of University Paris 7.

3. O. Sigaud. Des robots immergs dans la socit ? November 2015. Invited talk at the CE Industriel dAir France.

4. V. Padois. Design and control of collaborative robots: a focus on ergonomics and safety, November 2015. Panel Session on "360 on CNRS vision of FoF and Smart Cities" at the Colloque From Industry4.0 to Smart Cities.

5. V. Padois. Design and control of collaborative robots: a focus on ergonomics and safety, October 2015. Invited talk at the National Days on Robotics Research.

6. V. Padois. Whole-body compliant dynamical contacts for humanoids: the codyco project, June 2015. Invited talk at the National Days on Humanoid Robotics.

7. O. Sigaud. Des robots immergs dans la socit ? Mars, 2015. Invited seminar at la Semaine du Cerveau la Facult Saint-Charles de Marseille.

A.3.2 Other events

1. Darwin Lau. Generation of Dynamically Balanced Locomotion with Multiple Non-coplanar Contacts, June 2015. Presented at the National Days on Humanoid Robotics.

2. Ryan Lober. Tasks compatibility in whole-body control, June 2015. Presented at the National Days on Humanoid Robotics.

3. Aurlien Ibanez defended his PhD thesis on "Emergence of complex behaviors from coordinated predictive control in humanoid robotics" in september 2015.

4. Dcouverte du robot humanode iCub, October 2015. French national days for Science.

A.3.3 Talks at international conferences

1. Mingxing Liu presented the paper on "Generalized Projector for Task Priority Transitions During Hierarchical Control" at ICRA 2015.

2. Darwin Lau presented the paper on "Effective Generation of Dynamically Balanced Locomotion with Multiple Non-coplanar Contacts" at ISRR 2015.

3. Vincent Padois presented the paper on "Reactive whole-body control for humanoid balancing on non-rigid unilateral contacts" at IROS 2015.

4. Ryan Lober presented the paper on "Variance Modulated Task Prioritization in Whole-Body Control" at IROS 2015.

5. Darwin Lau presented the paper on "Minimization of the rate of change in torques during motion and force control under discontinuous constraints" at Robio 2015.

A.3.4 Publications

1. M. Liu, S. Hak, and V. Padois. Generalized projector for task priority transitions during hierarchical control. In Proceedings of the IEEE International Conference on Robotics and Automation, pages 768773, Seattle, USA, May 2015.

2. M. Liu, R. Lober, and V. Padois. Whole-body hierarchical motion and force control for humanoid robots. Autonomous Robots, 40(3):493504, 2016.

3. M. Liu and V. Padois. Reactive whole-body control for humanoid balancing on non-rigid unilateral contacts. In Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, pages 39813987, Hamburg, Germany, September 2015.

4. R. Lober, V. Padois, and O. Sigaud. Variance modulated task prioritization in whole-body control. In Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, pages 39443949, Hamburg, Germany, September 2015.

5. N. Perrin, D. Lau, and V. Padois. Effective generation of dynamically balanced locomotion with multiple non-coplanar contacts. In Proceedings of the International Symposium on Robotics Research, Sestri Levante, Italy, September 2015.

6. Y. Tan, D. Lau, M. Liu, P. Bidaud, and V. Padois. Minimization of the rate of change in torques during motion and force control under discontinuous constraints. In Proceedings of the IEEE International Conference on Robotics and Biomimetics (Robio), pages 26212628, Zhuhai, China, December 2015.

A.4 UB contributions to dissemination

1 invited talk, 1 editorial for journal special issue, 4 publications (1 journal, 2 international conferences, 1 workshop poster), 0 media coverage events.

A.4.1 Invited talks

1. Dr. Michael Mistry gave an invited workshop presentation on "Exploiting contact for whole-body physical human-robot collaboration" at the IEEE International Conference on Intelligent Robots and Systems (IROS 2015).

A.4.2 International events participation

1. Morteza Azad and Michael Mistry presented the poster: Manipulability of the Center of Mass, at the Workshop on Interpersonal Postural Interactions, Birmingham, 22 June 2015.

A.4.3 Talks at international conferences

1. Morteza Azad presented the paper on "Balance control strategy for legged robots with compliant contacts" at ICRA 2015.

2. Valerio Ortenzi presented the paper on "Projected inverse dynamics control and optimal control for robots in contact with the environment: A comparison" at IROS 2015

A.4.4 Editorial work

1. Mistry, M. Guest editor of Autonomous robots, Kluwer Academic Publishers, 1994-. ISSN 0929-5593. http://link.springer.com/journal/10514.

A.4.5 Publications

1. Ivaldi, S., Babic, J., Mistry, M., Murphy, R. Special issue on whole-body control of contacts and dynamics for humanoid robots. Autonomous robots, 2016, vol. 40, no. 3, 425-428.

2. Azad, M. and Mistry, M. Balance control strategy for legged robots with compliant contacts. IEEE International Conference on Robotics and Automation (2015), 4391-4396.

3. Ortenzi V, Stolkin R, Kuo JA, Mistry M. Projected inverse dynamics control and optimal control for robots in contact with the environment: A comparison, IEEE/RSJ International Conference on Intelligent Robots and Systems (2015), 4009-4015.

4. Azad, M. and Mistry, M. Manipulability of the Center of Mass, Poster at the Workshop on Interpersonal Postural Interactions, Birmingham, 22 June 2015.

A.5 JSI contributions to dissemination

2 invited talks, 1 editorial for journal special issue, 3 publications (2 journal, 1 internal conferences), 0 media coverage events.

A.5.1 Invited talks

1. Babic, Jan. Human-in-the-loop control of robots for industrial assembly tasks : invited talk, Omron Keihanna Technology Innovation Center, 7th September 2015, Kyoto, Japan.

2. Babic, Jan. Compliant robotic behaviour through human sensorimotor adaptation : presented at ICRA 2015, IEEE International Conference on Robotics and Automation, May 26th-30th, 2015, Seattle, Washington, USA.

A.5.2 Editorial work

1. Babic, J. Guest editor of Autonomous robots, Kluwer Academic Publishers, 1994-. ISSN 0929-5593. http://link.springer.com/journal/10514.

A.5.3 Publications

Ivaldi, S., Babic, J., Mistry, M., Murphy, R. Special issue on whole-body control of contacts and dynamics for humanoid robots. Autonomous robots, 2016, vol. 40, no. 3, 425-428.

Peternel, L., Noda, T., Petric, T., Ude, A,. Morimoto, J., Babic, J. Adaptive control of exoskeleton robots for periodic assistive behaviours based on EMG feedback minimisation. PloS one, ISSN 1932-6203, 2016, vol. 11, no. 2, 0148942-1-0148942-26.

Peternel, L., Petric, T., Babic, J. Human-in-the-loop approach for teaching robot assembly tasks using impedance control interface. In: 2015 IEEE International Conference on Robotics and Automation, May 26th-30th, 2015, Seattle, Washington, USA. ICRA 2015. Danvers: IEEE = Institute of Electrical and Electronics Engineers, cop. 2015, 1497-1502.

A.6 INRIA contributions to dissemination

Short summary:
○ 11 publications: 4 journals, 4 conference papers, 3 workshop papers
○ 2 international workshops: ICRA 2015 and BMVA 2015
○ 1 special issue organization in Autonomous Robots
○ dissemination of activies in several media

A.6.1 Invited talks

1. Ivaldi, S. (12/2015) Human-robot interaction with iCub. Invited talk at University of Plymouth, by Samantha Adams and Angelo Cangelosi.

2. Ivaldi, S. (10/2015) Social and physical interaction with the iCub robot. Invited talk at Technical University of Munich (TUM) by Karinne Ramirez and Gordon Cheng.

A.6.2 International events organization

Organization of international Workshops:

1. BMVA Workshop on Visual, tactile and force sensing for robot manipulation, December 9th 2015, London (UK), organized by L. Jamone and S. Ivaldi (`http://www.eventbrite.co.uk/e/bmva-workshop-on-visual-tactile-and-force-sensing-for-robot-manipulation-registration-16836320889`). The workshop was sold out (more than 80 participants).

2. ICRA 2015 Workshop ICRA 2015 Workshop "Get in touch! Tactile & force sensing for autonomous, compliant, intelligent robots", May 30th 2015, Seattle (USA), organized by S. Ivaldi, L. Jamone and B. Siciliano (`http://www.ausy.tu-darmstadt.de/Workshops/ICRA2015TactileForce`). The workshop had 147 registered participants.

A.6.3 Other events

◦ INRIA invited F. Nori (IIT) for a one-month research visit between January/February 2016.
◦ S. Ivaldi (INRIA) participated to the iCub Summer School (VVV15) with the CoDyCo team.

A.6.4 Talks at international conferences

1. Ivaldi, S. (2015) Social and physical interaction between humans and robots - perspectives for personal robotics assistants. Invited talk at NETT Workshop 2015 - Neural Engineering and related fields. Nancy, France.

2. Ivaldi, S. (2015) Multimodal object learning with iCub. BMVA Workshop on Visual, tactile and force sensing for robot manipulation, December 9th, London, UK.

3. Ivaldi, S. (2015) Individual differences and social signals during a human-robot assembly task. Workshop on Human-Friendly robotics, October 22th, Munich, Germany.

A.6.5 Editorial work

S. Ivaldi (INRIA), together with J. Babic (JSI) and M. Mistry (UB), was guest editor for the journal Autonomous Robots (Springer) for the special issue on Whole-body control of contacts and dynamics for humanoid robots.

The CoDyCo project is explicitly mentioned in the editorial article. A dedicated page is also on the CoDyCo website (`https://www.codyco.eu/2-default/48-special-issue-auro`).

A.6.6 Publications

Journals

1. Ivaldi, S.; Babic, J.; Mistry, M.; Murphy, R. (2016) Special Issue on Whole-body control of contacts and dynamics for humanoid robots. Autonomous Robots, vol. 40, n.3, pp. 425-428.

2. Lyubova, N.; Ivaldi, S.; Filliat, D. (2016) From passive to interactive object learning and recognition through self-identification on a humanoid robot. Autonomous Robots, vol. 40, n. 1, pp. 33-57.

3. Anzalone, S.; Boucenna, S.; Ivaldi, S.; Chetouani, M. (2015) Evaluating the engagement with social robots. International Journal of Social Robotics, vol. 7, n. 4, pp. 465-478.

4. Andries, M.; Simonin, O.; Charpillet, F. (2015) Localisation of humans, objects and robots interacting on load-sensing floors. IEEE Sensors Journal, Institute of Electrical and Electronics Engineers, PP (99), pp.12.

Conferences

5. Modugno, V.; Neumann, G.; Rueckert, E.; Oriolo, G.; Peters, J.; Ivaldi, S. (2016) Learning soft task priorities for control of redundant robots. Proc. IEEE International Conf. on Robotics and Automation (ICRA).

6. Calandra, C.; Ivaldi, S.; Deisenroth, M.P.; Peters, J. (2015) Learning Torque Control in Presence of Contacts using Tactile Sensing from Robot Skin. International Conf. on Humanoid Robots (HUMANOIDS).

7. Calandra, R.; Ivaldi, S.; Deisenroth, M.P.; Rueckert, E.; Peters, J. (2015). Learning Inverse Dynamics Models with Contacts, Proc. IEEE International Conference on Robotics and Automation (ICRA).

8. Traversaro, S.; Del Prete, A.; Ivaldi, S.; Nori, F. (2015). Inertial Parameters Identification and Joint Torques Estimation with Proximal Force/torque Sensing, Proc. IEEE International Conference on Robotics and Automation (ICRA).

Workshops

9. Ivaldi, S.; Peters, J.; Chetouani, M.; Lefort, S.; Zibetti, E.; Provasi. J. (2015). Individual differences and social signals during a human-robot assembly task. Proceedings of the 8th International Workshop on Human-Friendly Robotics - HFR 2015, p. 40.

10. Modugno, V.; Neumann, G.; Rueckert, E.; Oriolo, G.; Peters, J.; Ivaldi, S. (2016) Learning soft task priorities for control of redundant robots. Proceedings of the 8th International Workshop on Human-Friendly Robotics - HFR 2015, p. 39.

11. Calandra, R.; Ivaldi, S.; Deisenroth, M.P.; Rueckert, E.; Peters, J. (2015) Learning Dynamics Models of Contacts from Tactile Sensors. Proceedings of the ICRA 2015 Workshop on Force and tactile sensing.

Preprints

12. Ivaldi, S.; Lefort, S.; Peters, J.; Chetouani M.; Provasi, J.; Zibetti, E. Towards engagement models that consider individual factors in HRI: on the relation of extroversion and negative attitude towards robots to gaze and speech during a human-robot assembly task. Preprint at arXiv:1508.04603 [cs.RO].

A.6.7 Media coverage

- The CoDyCo experiments of human-robot physical interaction (collaboration INRIA & UPMC) are portrayed by Fiamma Luzzati in her web article on Le Monde (`http://lavventura.blog.lemonde.fr/2014/04/07/qui-a-peur-du-robot-google/`), then in her book “Le cerveau fait-il deux choses à la meme fois?”, Editions Delcourt (see Figure 32).
- Article in New Scientist, 21/10/2015

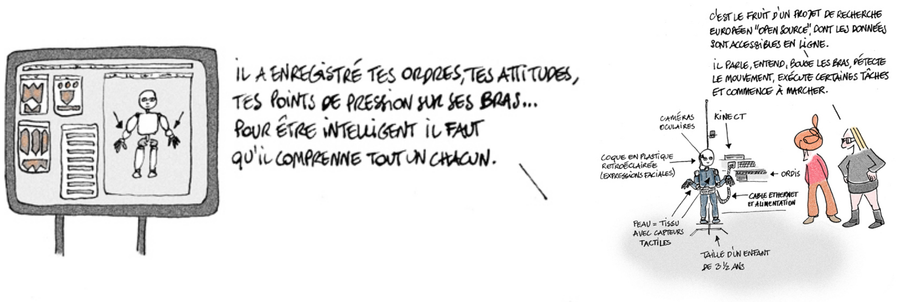

Figure 32: Samples from the comic of Fiamma Luzzati describing the physical human-robot interaction experiments with the iCub (INRIA/UPMC).

- Article in Cité Science, 29/10/2015
- Podcast interview for Interstices, 30/3/2016
- Article in La Semaine, 21/03/2016
- Article in Science et Vie Junior, 02/2016
- Article in Pour la Science, 03/2016