EUROBENCH "European Robotic Framework for Bipedal Locomotion Benchmarking"
H2020 Project - Grant Agreement No 779963

FSTP-2 Open Call "VALIDATION of the benchmarking framework"

Description of the available benchmarking scenarios

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 779963

LIST OF BENCHMARKING SCENARIOS

Benchmarking scenarios available for wearable robots 42
Walking with crutches 2
Characterization of user experience during exoskeleton-assisted walking 3
Characterization of the effects of the exoskeleton over muscle coordination 4
Sit-to-Stand, Stand-to-Sit 6
Walking/Standing on a moving surface 7
Walking/Standing during pushes 10
Ascending/Descending stairs 12
Walking over irregular terrains 13
Standing during manipulation 14
Ascending/Descending slopes 16
Walking on treadmill 18
Moving in narrow spaces 19

Benchmarking scenarios available for humanoids 42
Walking on flat ground 22
Pushing a shopping trolley or walker 23
Sit-to-Stand, Stand-to-Sit 24
Standing on a moving surface 26
Walking/Standing during pushes 27
Opening/Closing doors 28
Ascending/Descending stairs 30
Walking over irregular terrains 31
Walking over soft terrains 33
Overcoming obstacles 34
Standing during manipulation 35
Picking and carrying objects 36
Ascending/Descending slopes 38
Walking on a treadmill 39
Walking on laterally inclined surfaces 40
Moving in narrow spaces 41

Other available equipment 42
Force control characterization 42
Inertial sensors 44

Benchmarking scenarios available for wearable robots

Please, consider that the EUROBENCH framework is in constant evolution over time. The information included in this document has to be taken as a preliminary description of the scenarios, in order to allow participants to FSTP-2 Open Call to select them during proposal preparation.

Walking with crutches

Subproject: BULLET

Definition: Walking over a horizontal surface following a straight line with no irregularities nor perturbations with a pair of sensorized crutches.

TESTBED

Description: The setup is designed in order to assess the forces acting on the upper limbs due to the usage of a pair of sensorized crutches. The test requires using instrumented crutches over a horizontal surface with force platforms and mocap following a straight line with no irregularities nor perturbations. Gait must be performed after the volumetric scanning of the subject.

Figure:

Equipment:

- **Sensors**
    - Volumetric scanner
    - Motion capture
    - Force platform
    - Instrumented crutches - IMUS, camera, pressure sensor

PROTOCOLS

Protocol's name	Minutes per run	Description
Walking on straight lines with instrumented	12	The subject has to walk along a straight line for 10 m, without any particular instruction, using instrumented crutches. The crutches height should be adjusted to the subject before the test. Motion capture should be available, as well as force platforms, along the

crutches, mocap and force platforms		path. A preliminary assessment of the subject's anthropometric data is required. Data collection is started at the beginning of the walk and stopped after each walk.
Walking on straight lines with instrumented crutches	12	The subject has to walk along a straight line for 10 m, without any particular instruction, using instrumented crutches. The crutches height should be adjusted to the subject before the test. Data collection is started at the beginning of the walk and stopped after each walk.

PERFORMANCE INDICATORS (PIs)	
Name	**Description**
Peak_load_left/right	This PIs calculates mean and standard deviation of the left/right crutch peak loads (maximum force value for each stride cycle), and step number.
RMS_load_left/right	Root mean square value of the left/right crutch force.
Stance_time_left/right	This PIs calculates mean and standard deviation of the left/right stance time and step number.
Peak_load_shoulders _left/right	Vector of 13 elements containing mean and standard deviation of the left/right shoulder, force X, force Y, force Z, torque X, torque Y, torqueZ peaks (maximum value for each stride cycle), and step number expressed in the fixed lab reference frame.
RMS_load_shoulders _left/right	Vector of 6 elements containing 3 force components (X, Y, Z) and 3 torque components (X,Y,Z) of left/right shoulder RMS load expressed in the fixed lab reference frame.

Characterization of user experience during exoskeleton-assisted walking

Subproject: EXPERIENCE

Definition: The protocol analyzes overground walking supported by an assistive lower limb exoskeleton. The aim is the comprehensive and systematic assessment of user subjective experience during exoskeleton-assisted walking. This is achieved by administering a novel multi-factor questionnaire to derive psychological indicators and by measuring physiological information to compute psychophysiological indicators.

TESTBED

Equipment:

- **Sensors**
  - Galvanic skin response measurement
  - Heart rate
  - Respiration rate
- **Questionnaires**

PROTOCOLS

Protocol's name	**Minutes per run**	**Description**

User-centered assessment of exoskeleton-assisted overground walking	80	Each subject is monitored during a first phase in seated condition, then standing while wearing the exoskeleton and finally walking with it. In the end, a questionnaire is administered.
Exoskeleton-assisted treadmill-based walking	80	Each subject is monitored during a first phase in seated condition, then standing while wearing the exoskeleton and finally walking over a treadmill with it. In the end, a questionnaire is administered.

PERFORMANCE INDICATORS (PIs)

Name	**Description**
usability	The extent to which the exoskeleton can be used by the users to achieve specific goals with effectiveness, efficiency and satisfaction in this specified context of use. A high value of this PI indicates that the robot is highly usable.
acceptability	It relates to how the users perceive robots when interacting directly with them and how much you would be willing to introduce it into your everyday life. A high value of this PI indicates that the robot is highly acceptable.
perceptibility	It evaluates the effects and influences that walking with the exoskeleton has on your emotions, perceptions and quality of life. A high value of this PI indicates that the robot positively influences emotion, perception and quality of life.
functionality	It measures the perception of the characteristics of the exoskeleton in terms of ease of learning, flexibility of interaction, reliability and workload. A high value of this PI indicates positive features of the robot in terms of analyzed aspects.
stress	It is defined as a state of mental or emotional strain caused by adverse circumstances. A high value of this PI indicates that the robot use is stressful.
fatigue	It can be described as a type of distress generally conditioned by the exhaustion of one's muscles due to the execution of a task. A high value of this PI indicates that the robot induces fatigue.
energy_expenditure	It is the amount of energy that is needed to carry out physical functions. A high value of this PI indicates that the robot use requires high effort.
attention	It refers to the degree to which the user is consciously and continuously involved in the task. A high value of this PI indicates that the robot use requires high attention.

Characterization of the effects of the exoskeleton over muscle coordination	**Subproject: PEPATO**

Definition*:* The rationale of this scenario is to characterize gait performance at the level of muscle coordination. It aims at characterizing how a user adapts to the exoskeleton walking and how the exoskeleton perturbs the operator's control strategy and affects the spinal muscle coordination output. The proposed outcomes will provide important information about the neural control strategy and spinal locomotor output during walking with the exoskeleton that will complement other performance indicators. While the scenario involves walking on a treadmill, it may also be extended to overground walking, walking on inclines, walking on uneven terrain.

Equipment:

- **Sensors**
  - EMG
  - Motion capture system
  - Force platform
- **Actuators**
  - Treadmill

PROTOCOLS		
Protocol's name	**Minutes per run**	**Description**
Walking on a treadmill at 3 speeds	30	Walking on a treadmill at a constant speed: 2, 4 and 6 km/h. At least 10 consecutive strides should be recorded for each speed condition.

PERFORMANCE INDICATORS (PIs)	
Name	**Description**
muscle_synergy_number	The number of muscle synergies best describing the EMG data (for each speed). The larger the number of synergies the higher the dimensionality/complexity of muscle control.
emg_reconstruction_quality	Reconstruction quality (R2) of EMG patterns from muscle synergies (for each speed). The larger the R2, the better the reconstruction of EMGs with muscle modules.
pattern_fwhm	FWHM (full width at half maximum) - duration estimate of basic patterns (for each speed). Wider basic activation patterns are typically associated with unstable walking conditions.
pattern_coa	Centre-of-activity (CoA) of basic patterns (for each speed). The difference between CoA with that of the reference database would indicate significant changes in the timing of muscle module activation during walking in the exoskeleton.
muscle_module_similarity	The degree of similarity of muscle synergies and basic patterns with the reference group (4 module clusters for each speed) = the mean distance to the nearest module cluster center (measured in standard deviations). The smaller the distance, the smaller the deviation of the muscle modules (neural control) of exoskeleton walking from those of normal walking.
matching_standard_reference_index	This index is not PI but it is used for aggregation (inter-subject scoring) of the following PIs: pattern_fwhm, pattern_coa, muscle_module_similarity. Each value corresponds to the index of the nearest module in the reference database. If the value is missing (NaN), the module does not match any in the reference.
motor_pool_max_activation_timing	Timing of the main loci of MN activity: timing of maximum activation of sacral (S1+S2) and upper lumbar (L3+L4) motor pools (for each speed). Alterations in the relative activation timing of sacral and lumbar motor pools represent important biomarkers of changes in the spinal locomotor output. The larger its deviation from the reference database, the more different the segmental control of walking in the exoskeleton is. An abnormal spatiotemporal integration of activity in specific spinal segments may result in a risk for failure or abnormalities in gait recovery.
motor_pool_fwhm	FWHM of activation of sacral and upper lumbar spinal motor pools (for each speed). Widening of spinal segmental output represents an important physiological marker of pathological gait and/or unstable walking conditions.
motor_pool_coactivation	Co-activation index of sacral and upper lumbar motor pools (for each speed). Higher coactivation of sacral and lumbar motor pools may characterize abnormal functioning of the spinal locomotor output.

motor_pool_similarity	The degree of similarity (correlation) of activation of sacral and lumbar motor pools with respect to the reference group. The higher the similarity, the smaller the deviation of the neural control of exoskeleton walking from that of normal walking.

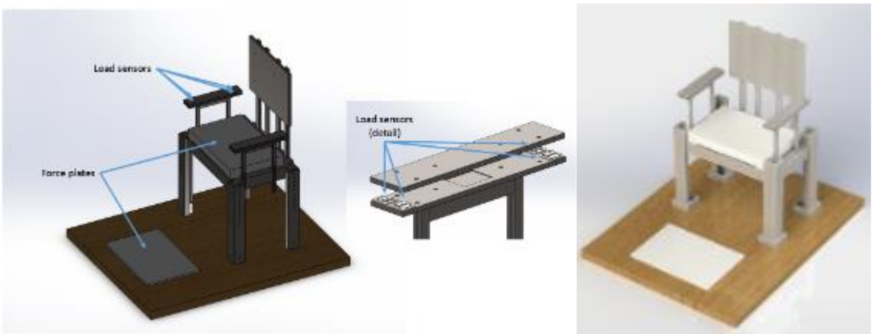
Sit-to-Stand, Stand-to-Sit	**Subproject:** ***BENCH***

Definition*:* Sit-to-stand (STS) is an important task for assessing dynamic balance and lower limb coordination. STS is important also for assessing the performance of wearable lower-limb exoskeletons for assistance and humanoid robots that imitate human movements. These protocols and the associated PIs aim at the assessment and benchmarking of the sit-to-stand gesture in intact and impaired individuals, in human/exoskeleton systems and in humanoid robots.

TESTBED

Description: The testbed measures the reaction forces by a force plate placed in front of the chair and the reaction forces in the forearms by two force sensors (one in each arm of the chair). A third force plate is placed on the seat.

Figure:



Equipment:

- **Sensors**
  - Load sensors
  - Force plates
  - IMU sensors: 3D accelerometers and gyroscope.

PROTOCOLS

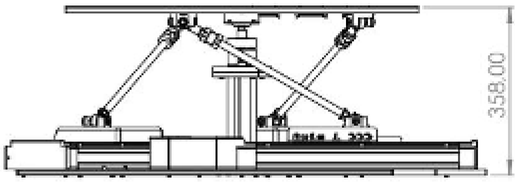
Protocol's name	Minutes per run	Description
5 sit to stand	2	Measures how long it takes to complete 5 full STS cycles, starting from a sat position and reaching again the initial position. The subject sits on the device in a comfortable position with the arms across the chest leaning on the back rest. At the "go" signal, the subject is instructed to perform 5 complete sit-to-stand cycles as rapidly as possible, without touching the back rest between consecutive cycles, and reaching the full extended upright posture at the end of each standing.
30 seconds sit to stand	2	**Definition:** Measures how many full STS cycles are completed within a 30s time frame, starting from a sat position. The subject sits on the device in a comfortable position with the arms across the chest leaning on the back rest. At the "go" signal, the subject is instructed to perform as many complete sit-to-stand cycles as possible,

		without touching the back rest between consecutive cycles, and reaching the full extended upright posture at the end of each standing. A stop signal is communicated at the end of the 30s time frame.

PERFORMANCE INDICATORS (PIs)	
Name	**Description**
5STS duration	Time to execute 5 times STS. The lower the duration, the higher the performance.
30s STS number of repetitions	How many STSs are executed in 30 seconds. The higher the number, the higher the performance.
STS subphases duration	Duration of each STS subphase (i.e., stance, stance-to-seat, seat, sit-to-stand)
Stand and sit stability	Distance traveled by the CoP over a 10 seconds period, normalized by the subject's height.
Time needed for unidirectional load transfer	Time to transfer load from one plate to the other, only applicable during free STS.
Unidirectional load transfer overshoot	Distance between the quiet standing CoP position and the local maxima of anteroposterior and latero-lateral CoP during transition.
Time spent on backrest	Average time spent on the back of the seat.
Range of motion	Range of sagittal motion.
Peak joint moments	Peak joint moments.

Walking/Standing on a moving surface	**Subproject:** ***BEAT***
Definition*:* Perform walking task or balance on the robotic movable platform in both unperturbed and perturbed conditions.	
TESTBED	
Description: The BEAT is placed in a pit so that the top be level with the ground. The top platform moves by three actuators to perturbate the ground conditions of the patient. The machine has a force plate in the top surface to measure the ground reaction force while the platform moves. **Figure:**	





Equipment:

- **Sensors**
  - Inertial sensors
  - Optoelectronic system
  - Electromyography
- **Actuators**
  - Moving platform

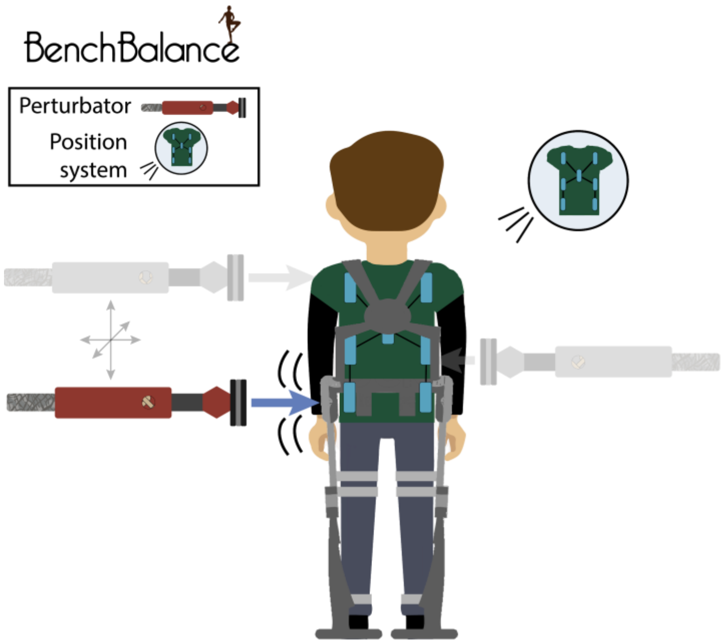
PROTOCOLS		
Protocol's name	**Minutes per run**	**Description**
Stepping on place - even surface	2	The subject performs stepping on place with the platform locked for 60s.

Stepping on platform - uneven surface	2	The subject performs stepping on place with the platform unlocked for 60 s. The protocol allows simulating real life conditions, such as walking on uneven streets.
Static Balance - even surface	1	The subject stands on the locked platform with open or closed eyes.
Static Balance - uneven surface	1	The subject stands on the unlocked platform with open or closed eyes. This protocol permits simulating real life conditions, such as wearing an exoskeleton on a bus where the upright position can be perturbed by a sudden braking.
Step perturbation - even surface	5	The subject stands on the platform and reacts to a step perturbation with the platform set in position control. Perturbations are provided along 8 different directions, according to the cardinal points.
Step perturbation - uneven surface	5	The subject stands on the platform and reacts to a step perturbation with a platform set in impedance control, it means that the platform is compliant during the perturbation. Perturbations are provided along 8 different directions, according to the cardinal points.
Sinusoidal perturbation - even surface	5	The Subject stands on the platform and reacts to a sinusoidal perturbation with the platform set in position mode. Perturbations are provided along 4 different directions (anterior-posterior, medio-lateral, vertical and a mixed direction of the others).

PERFORMANCE INDICATORS (PIs)	
Name	**Description**
Mean Range of Motion	Mean value of the joint angle Range of Motion. Smaller values indicate a reduction of the physiological movement of the subject.
Coefficient of Variation	Coefficient of Variation related to the joint angle ROM. Ratio between standard deviation and mean value of ROM across different strides. Greater value of CoV represents a greater variability of the kinematics, which leads to a worsening of the subject motor performance.
Range of Motion in different perturbation direction	Represents the range of motion of considered angles in the eight directions of step perturbation. The eight directions are: North (N), North-East (NE), East (E), South-East (SE), South (S), South-West (SW), West (W), NorthWest (NW). Smaller values indicate a reduction of the physiological movement of the subject
Path Length of the Centre of Pressure	It represents the distance covered by the centre of pressure considering all directions. Greater value indicates greater instability.
Path Length of the Centre of Pressure in antero-posterior direction	It represents the distance covered by the centre of pressure considering only the anterior-posterior direction. Greater value indicates greater instability in anteroposterior direction.
Path Length of the Centre of Pressure in medio-lateral direction	It represents the distance covered by the centre of pressure considering only the mediolateral direction. Greater value indicates greater instability in mediolateral direction.
Area of the confidence ellipse	It represents the area of the confidence ellipse containing the 95% of the point covered by the centre of pressure. Greater value indicates greater instability during the task.

Path Length of the Centre of Pressure after perturbation	It represents the distance covered by the centre of pressure reported for each perturbation direction. Greater value indicates greater instability.
Area of the confidence ellipse after perturbation	It represents the area of the confidence ellipse containing the 95% of the point covered by the centre of pressure reported for each perturbation direction. Greater value indicates greater instability during the task.
Number of muscle synergies of left/right side	It represents the number of muscle synergies. Lower number of muscle synergy indicates an optimization of the muscle coordination by the Central Nervous System when tasks are performed by healthy subjects or an impossibility to enrol all the left/right muscle synergies in subjects with neuromuscular pathologies.
Platform angle overshoot	It represents the overshoot of the platform angle after the subject's reaction under step perturbation in all the imposed directions. Lower value indicates a better anticipatory postural adjustments capability of the subject.
Final value of the platform angle	It represents the final angle of the platform angle after the subject's reaction under step perturbation computed as the mean value of the last 50 samples in all the imposed directions. Value close to zero indicates the perfect capability of the subject to bring back the platform in the neutral position.
Range of motion of the platform angle	It represents the range of motion of the platform angle after the subject's reaction under step perturbation computed during the last 1.5 s of the task for all directions. Lower value indicates a greater stability after the perturbation reaction.
Gain index	It represents the gain ratio between the sinusoidal perturbation signal imposed and the signal of the recorded segment. It represents how the segment follows the perturbation in terms of amplitude. The considered angles will be: neck, trunk and pelvis. All the angles are referred to the transverse plane.
Phase shift	It represents the phase shift between the sinusoidal perturbation signal imposed and the signal of the recorded segment. It represents how the segment follows the perturbation in terms of phase. The considered angles will be: neck, trunk and pelvis. All the angles are referred to the transverse plane. A result equal to 0 indicates that examined segment is in perfect phase with the perturbation; negative value indicates phase delay (lower value=greater delay); positive value indicates phase anticipation (greater value=greater anticipation)

Walking/Standing during pushes	**Subproject:** ***BenchBalance***
Definition*:* Standing wearing an exoskeleton and maintaining balance reacting to well-defined external perturbations manually provided by an experimenter.	
TESTBED	
Description: The patient wears a sensorized vest that can register the position of the external perturbation. There are lineal actuators that provide external perturbations in the patient. **Figure:**	



Equipment:

- **Sensors**
  - Motion capture system
  - Perturbator - Inertial sensors.
  - Smart garment - Pressure sensors based on optical fiber.
- **Actuators**
  - Perturbator

PROTOCOLS		
Protocol's name	**Minutes per run**	**Description**
Perturbed balance assessment	30	The subject is standing wearing or not an exoskeleton. The perturbed balance is assessed and in particular the capability of recovering from measured manually delivered pushes. The subject receives perturbations by means of perturbator and has to recover from them without taking a step.

PERFORMANCE INDICATORS (PIs)	
Name	**Description**
body_sway	The maximum body sway angle in response to a perturbation. - For anteroposterior perturbations: considering in the sagittal plane the line from the CoM to the ankle joints rotation axis, the body sway is calculated as the maximum angle between this line at rest and the same line after the perturbation. - For lateral perturbations: considering in the frontal the line from the CoM intersecting the ankle joints rotation axis in the middle point between the feet, the body sway is calculated as the maximum angle between this line at rest and the same line after the perturbation. A high value of the body sway indicates less ability of the subject to maintain the balance.
recovery_time	Time to recover from a perturbation. This is calculated as the time needed for the CoM to go back to the rest position (i.e. when the sway angle velocity becomes lower than a threshold) after the perturbation. A high value of the recovery time indicates less ability of the subject in

	maintaining the balance.

Ascending/Descending stairs

Subproject: ***STEP BY STEP***

Definition: Systematic test by a stairs-based testbed evaluation protocols

TESTBED

Description: Active stairs that allow yo regulate the height of the top platform and the inclination of the stairs. When the stairs change its height, the steps stay parallel to the ground during the movement.

Figure:

Equipment:

- **Sensors**
  - Instrumented stair - Force platforms
  - IMUs
  - EMG
  - Cronometer
- **Actuators**
  - Speaker/headphone

PROTOCOLS

Protocol's name	Minutes per run	Description
Dual Task protocol	15	Measures the user's cognitive-motor interference while accomplishing a motor task with the exoskeleton and doing a cognitive task.
User Exoskeleton Interaction Observation	10	It describes the quality of the interaction occurring between the wearer and the lower-limb exoskeleton. The data collection is performed by experimenters based on a quantitative checklist of both participant's and exoskeleton's behaviour.
Local Perceived Pressure Questionnaire	5	The questionnaire measures the subjective evaluation of musculoskeletal pressure applied by the exoskeleton to the user.

Stairs_Ergonomics_Protocol	25	Mocap acquisition in stair ascending and descending over the testbed in order to characterize human movements. Different parameters will be computed: total time ascending and descending, subphases of stair climbing/descend and kinematics.
Stairs_EMG_Protocol	40	This protocol aims at assessing the subject's motor control ability in stair ascending/descending through the analysis of the EMG activation pattern. The sEMG of Tibialis Anterior (TA), soleus (SOL), rectus femoris (RF), and hamstring muscles (HAM) will be collected bilaterally.

PERFORMANCE INDICATORS (PIs)

Name	**Description**
stride_time_right/left	The right/left stride time is the time elapsed between two consecutives right/left foot strikes.
stance_time_right/left	The right/left stance time is the time elapsed between right/left foot strike and right/left toe off.
swing_time_right/left	The right/left swing time is the time elapsed between right/left foot toe-off and right/left strike.

Walking over irregular terrains

Designed by EUROBENCH

Definition: Walking through different configurable irregular terrains.

TESTBED

Description: The testbed is conformed by a flat platform to which a set of modules can be attached to conform five different irregular conditions and three soft terrains.

Figure:

Equipment:

- **Sensors**
  - Optical motion capture system
  - IMUs

PROTOCOLS

Protocol's name	**Minutes per run**	**Description**

Walking through irregular terrains	80	The subject must pass through each one of the irregular terrains at a comfortable speed.

PERFORMANCE INDICATORS (PIs)

Name	Description
margin_of_stability	Analogous parameter to the condition of standing stability which states that the center of mass (CoM) should be within the base of support (BoS). The extrapolation to dynamic stability states that the position of the vertical projection of the CoM (PCoM) plus its velocity times a factor (extrapolated center of mass position (XCoM)) should be within the BoS.
gait_deviation_index	Scaled distance between 15 gait feature scores for a subject and the average of the same 15 gait feature scores for a control group of typically developing (TD) children.
walk_ratio	Defined as the division of step length by cadence. It is used to measure overall gait control.
gait_parameters_variability	Difference between the value of a gait parameter when walking without the exoskeleton and the value of the same gait parameter obtained when walking wearing the exoskeleton.
ratio_index	Defined as the division of a gait parameter by the same gait parameter of the contralateral limb. It is used for quantifying gait symmetry.

Standing during manipulation

Designed by EUROBENCH

Definition*:* Standing while reaching, grasping and manipulating objects with the upper limbs.

TESTBED

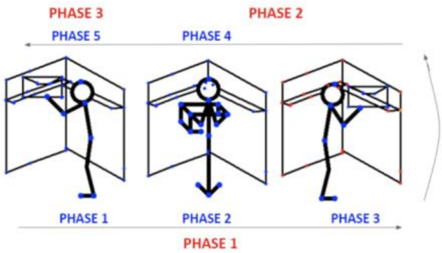
Description: The testbed is a non-reflectant modular structure consisting of a fixed frame and mo- bile bars, in order to be easily adjusted to the height of the knee and of the shoulder of each subject. On one hand, the fixed body is formed by 3 vertical bars, 2 of them are 1.75 metres-long and the third one is 2 metres-long; connected to 4 horizontal 1 metre-long bars at their ends. Moreover, 2 more 1 metre-long bars are used to close the square at floor-level in order to give more consistency to the structure. On the other hand, the mobile part is made up of four 1 metre-long bars fit in the fixed frame (2 bars per wall of the structure). These bars are mobile thanks to its design: a guiding system which allows moving the horizontal bar along the vertical ones with ease and 2 toggles on each bar to avoid time-consuming screwing tasks. On top of each mobile bar and in the middle region of it, there is a 30x50 cm wooden shelf screwed to the bar, where the box should be placed during the lifting and the lowering phases. Also two plastic boxes (as the objects to manipulate) and a set of weights (to change their mass) are provided.

Figure:

Equipment:

- **Sensors**
  - Optical motion capture system
  - IMUs

PROTOCOLS

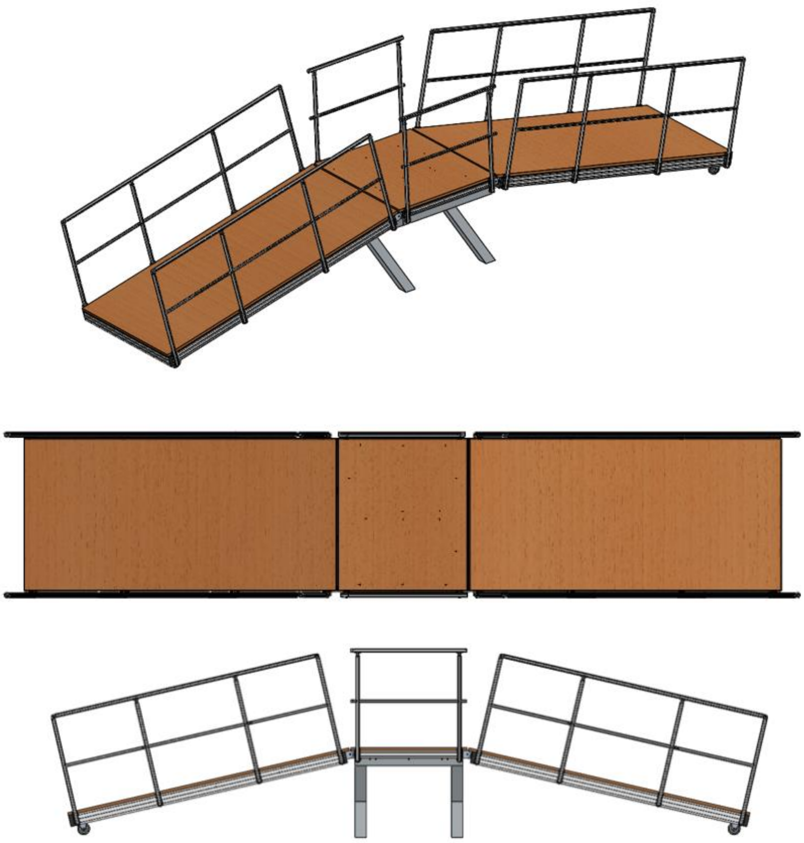
Protocol's name	Minutes per run	Description
Lower-lifting sagittal plane	5	Lifting a box, which could be empty or loaded with the 10% of the subject's weight, its placement on a horizontal support assembly at different heights, and the final lowering phase in order to bring the box back to its initial position. The subject must have performed 3 lifts with an empty box as well as 3 lifts with a loaded one. This experiment is performed in the sagittal frame and between sagittal and frontal planes.  (a) Floor-to-Knee. (b) Floor-to-Shoulder. (c) Knee-to-Shoulder.
Lateral load transfer	5	Lifting a box, which could be empty or loaded with the 10% of the subject's weight, its placement on a horizontal support assembly at different heights involving sagittal rotation, and the final lowering phase in order to bring the box back to its initial position. The subject must have performed 3 lifts with an empty box as well as 3 lifts with a loaded one. 

PERFORMANCE INDICATORS (PIs)

Name	Description

Range of Motion (RoM)	Ratio of joint angles calculated as the exoskeleton condition relative to the free condition, with load and lift type factors constant within a particular ratio. The joints considered are: spine, hip, knee, ankle, shoulder and elbow.
Anteroposterior Deviation	M. Alamoudi, "Investigation and Analysis of the Effects of Manual Lifting and Carrying Activities on Postural and Gait Stability in Normal Subjects," 2017. Dissertation found in the Research repository of Miami University
Mediolateral deviation	M. Alamoudi, "Investigation and Analysis of the Effects of Manual Lifting and Carrying Activities on Postural and Gait Stability in Normal Subjects," 2017. Dissertation found in the Research repository of Miami University
Total deviation	M. Alamoudi, "Investigation and Analysis of the Effects of Manual Lifting and Carrying Activities on Postural and Gait Stability in Normal Subjects," 2017. Dissertation found in the Research repository of Miami University
Anteroposterior postural stability	M. Alamoudi, "Investigation and Analysis of the Effects of Manual Lifting and Carrying Activities on Postural and Gait Stability in Normal Subjects," 2017. Dissertation found in the Research repository of Miami University
Mediolateral postural stability	M. Alamoudi, "Investigation and Analysis of the Effects of Manual Lifting and Carrying Activities on Postural and Gait Stability in Normal Subjects," 2017. Dissertation found in the Research repository of Miami University
Performance time	The time to complete the task has been calculated by dividing the number of frames by the sampling frequency. In addition, the time spent in each of the phases.
Spinal Loads Estimation	L4-L5 and L5-S1 shear and compression forces are estimated by using the coefficients of the simplified regression equations provided in the Supplementary Material of [F. Ghezelbash et al., "Subject-specific regression equations to estimate lower spinal loads during symmetric and asymmetric static lifting," Journal of Biomechanics, vol. 102, p. 109550, 2020.].

Ascending/Descending slopes	**Designed by EUROBENCH and UDBenchmarking subproject**
Definition: The stability of bipedal locomotion is challenged when walking on an inclined surface. Changes of surface orientation asks for adequate adaptation to the new situation, and therefore requires enhanced control of fore-aft and lateral stability. By assessing the control of gait stability and foot placement strategies, the gait stability of people using wearable robotic assistive devices can be quantified.	
TESTBED	
Description: The trestbeds consists of a flat surface that is attached to a lift. This set-up allows for changes in walking surface angle by inclining the flat board. **Figure:**	



Equipment:

- **Sensors**
  - Optical motion capture system
  - IMUs
  - sensorized insoles
- **Actuators**
  - Lift

PROTOCOLS

Protocol's name	**Minutes per run**	**Description**
Slope walking up	20	Participants walk up the slope with an increase in the slope angle in each run. Three dimensional full-body kinematics of participants are recorded using a Vicon motion capture system.
Slope walking down	20	Participants walk down the slope with an increase in the slope angle in each run. Three dimensional full-body kinematics of participants are recorded using a Vicon motion capture system.

PERFORMANCE INDICATORS (PIs)

Name	**Description**
Mediolateral Margin of Stability	Euclidian distance from the extrapolated centre of mass to the base of support in the medio-lateral direction

Anteroposterior Margin of Stability	Euclidian distance from the extrapolated centre of mass to the base of support in the anterior-posterior direction
Local Divergence Stability [LDS]	Quantifying the rate of separation of nearest neighbour trajectory (i.e., position) in a phase space. A larger LDS suggests a less stable gait pattern.
Left Step Length	Distance of the centre of gravity of the left foot to the centre of gravity of the right foot in antero-posterior direction at left heel strike.
Right Step Length	Distance of the centre of gravity of the right foot to the centre of gravity of the left foot in antero-posterior direction at right heel strike.
Stride Time	Time between heel strike of one leg to the next heel ipsilateral heel strike.
Left Step Width	The distance of the centre of gravity of the left foot to the centre of gravity of the right foot in mediolateral direction at left heel strike.
Right Step Width	The distance of the centre of gravity of the right foot to the centre of gravity of the left foot in mediolateral direction at right heel strike.
Foot Placement Estimates	The euclidean distance from the estimated position of foot placement to come to a stable stance within one step to the actual step position, i.e., a smaller distance suggests a more stable gait.
Explained Variance by a Linear Foot Placement Model	The goodness of fit of a linear regression model for foot placements. A higher score suggests less active control, which indicates better performance.

Walking on treadmill

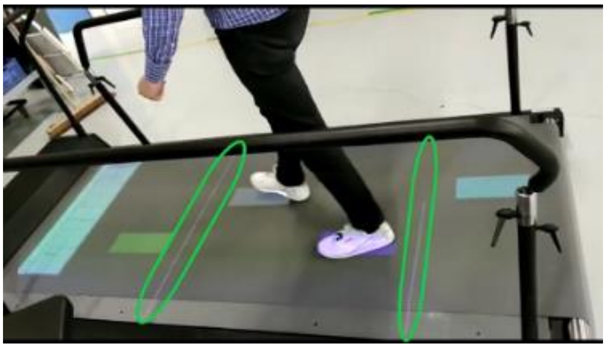
Subprojects: BeStable and TREADMILL

Definition*:* The subject must walk in a treadmill where stepping targets can be visually projected onto in unexpected timings and patterns. The prescribed stepping patterns can emulate responses to mechanical balance perturbations, such as mediolateral and anteroposterior pushes to the pelvis.

TESTBED

Description: Walking on a treadmill and stepping on targets projected onto its surface in unexpected patterns to perturb balance. Outcome measures include the target hit rate, spatio-temporal stepping characteristics (e.g., stepping length, width, and time), and ground reaction forces.

Figure:



Equipment:

- **Sensors**
    - Optical motion capture system
    - IMUs
    - Instrumented treadmill - Force plates
- Actuators
    - Instrumented treadmill
    - Projector

PROTOCOLS

Protocol's name	Minutes per run	Description
Visually-cued stepping perturbations on a treadmill	25	The subject will wear IMU sensors on the feet and walk on an instrumented treadmill at a prescribed speed. They will be asked to step on targets appearing on the surface of the treadmill in unexpected locations and timings. The characteristics of the stepping patterns will be recorded.

PERFORMANCE INDICATORS (PIs)

Name	Description
step_error	Minimum distance between foot placement (centre of pressure) and target centre. Values for both anteroposterior and mediolateral directions.
step_length_right/left	Length of a step for the right/left leg
step_width_right/left	Width of a step for the right/left leg
stride_time_right/left	Also known as the gait cycle duration. Is defined as the time elapsed between the first contact of two consecutive footsteps of the same foot
step_time_right/left	The step time is the time between heel strike of one leg and heel strike of the contralateral leg.

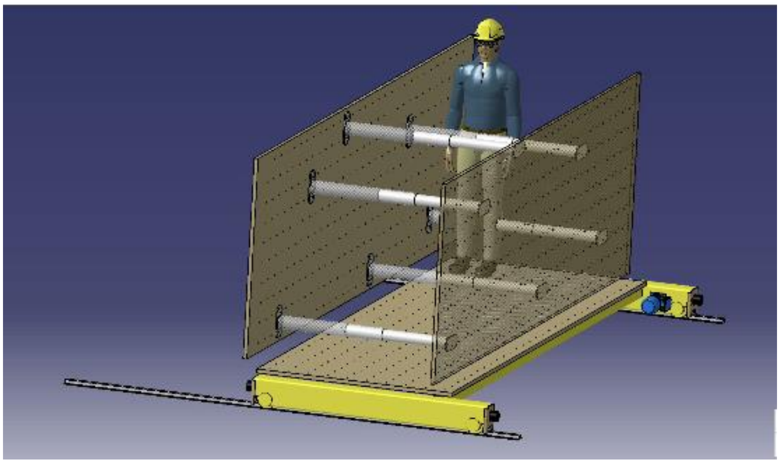
Moving in narrow spaces

Subproject: TESTED

Definition: Due to the workspace optimization techniques and lean manufacturing, the modern workstations are narrow. TestEd can help to simulate these workstations to test wearable technology new concepts and prototypes. Its modular design and flexibility can help to quickly prepare the intended workstation.

TESTBED

Description: This testbed simulates the industrial narrow space workstations. It can help to reconfigure its length and width hence there are many configurations that can be tested. The inbuilt sensors and actuators ensure the data collection and safety of the subjects. It demonstrates three configurations taken from the automotive, construction and aeronautical industry.
Figure:



Equipment:

- **Sensors**
  - Instrumented walls
  - Motion Capture System
  - Force Plate
  - Polar H10

PROTOCOLS		
Protocol's name	**Minutes per run**	**Description**
Industrial Use-Cases in Narrow Spaces	2	In sitting/standing posture, with both feet on the floor of the testbed with truck bending/straight. The subject performs a circular inspection of a profile placed on the force sensitive wall of the testbed. The subject will hold the quality control gauge in one hand to find the distance between the gap and flush of the profile.
Industrial Use-Cases in Narrow Spaces	1	In a standing posture, with both feet on the floor of the testbed. The subject performs a horizontal movement with the tip of the Tig welding torch while holding the stick in another hand.
Industrial Use-Cases in Narrow Spaces	5	In a sitting posture, with both feet on the floor of the testbed with a straight truck, the subject performs installation of two curved sheets on the force sensitive wall and then fastens the sheets in a vertical straight line with an electrical screwdriver. The fastening will be performed with one hand holding the screw driver while the second hand guides the screw.

PERFORMANCE INDICATORS (PIs)	
Name	**Description**
hrMonitoring	This metric is based on the RR interval (time between successive heart beat) analysis for short-term intervals. The PI is composed of four values: the RMSSD (Root mean square of the successive differences), the SDNN (Standard deviation of the NN (R-R) intervals), NN50 (The number of adjacent NN intervals that differ from each other by more than 50 ms) and the PNN50 proportion of NN50 divided by the total number of NN (R-R) intervals). The obtained values can be compared with state of the art tables at: 1. https://hrvcourse.com/wp-content/uploads/2016/07/HRVAgeGender-Table-1080x497.png 2. https://journals.plos.org/plosone/article/file?id=10.1371/journal.pone.0118308&type=printable
metabolic Cost	This metric is based on the analytical prediction of the metabolic rate in kilocalories (kcal) of a human performing static and dynamic tasks. The user can select two type of tasks: 1. Static task (postureMaintain) that calculates the metabolic cost based on body static postures.

	The user can further select the three sub-options based on the task under investigation: 1. Sitting or 2. Standing or 3. Standing and Bending 2. Dynamic task (otherTasks) that calculates the metabolic cost based on dynamic tasks. The user can further select the twenty-two (22) sub-options based on the task under investigation: 1: Stoop lift, 2: Squat lift, 3: One hand lift, 4: Arm lift, 5. Stoop lower, 6. Squat lower, 7. Arm lower, 8. Walking, 9. Carrying, loads held at arm's length at sides (1 or 2 hands), 10. Carrying loads held against thighs or against waist, 11.Holding, at arm's length, against thighs or at sides(2 hands), 12. Holding against the waist, 13. Holding, at arm's length in one hand, 14. Pushing/pulling, at bench height (0.8 meters), 15. Pushing/pulling, at 1.5 meters height, 16. Lateral movement of arms of 180 degrees, 2 hands, 17. Lateral movement of arms of 180 degrees, 1 hand, 18. 90 degrees arms lateral movement, standing, 1 or 2 hands, 19. 90 degrees arms lateral movement, sitting, 2 hands, 20. 90 degrees arms lateral movement, sitting, 1 hand, 21. Forward movement of arms, standing, 1 or 2 hands, 22. Forward movement of arms, sitting, 1 or 2 hands The metric results can help the user to combine selected sub-task metabolic costs in kcal and quickly check the metabolic load of the task under investigation.
chrono	Time to complete the task.
balance	This metric is based on the DPSI (Dynamic Posture Stability Index) that assesses the subject's ability to maintain balance while transforming between static to dynamic stance. The PI is composed of six values: areaDPSI (sum of all the DPSI at all time steps), areaDPSIvsTime (normalized sum of all the DPSI with respect to time), maxat (maximum DPSI value during the experiment), maxTime (time at maximum DPSI value), minat (minimum DPSI value during the experiment) and mixTime (time at minimum DPSI value). The obtained values can be compared with state of the art table [see article table 1] (subjected to the same measurement protocol of the following article): https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1323292/
range of Motion	This metrics will provide the user to check if the applied joint angles are within the allowable permissible range established by the standards. The PI is composed of joint-wise three values: counter_r_[joint name] (this counter represents how many times the joint angles remains within or outside the permissible limits), maxVal_r_[joint name] (this value represents the maximum value of the joint angle during the experiment) and minVal_r_[joint name] (this value represents the minimum value of the joint angle during the experiment). The user can select the allowable joint angle and insert in the PI. Following are the main reference that can provide such values: https://books.google.com/books?hl=en&lr=&id=TSluDQAAQBAJ&oi=fnd&pg=PR1&dq=measurement+of+joint+motion&ots=2gaQs8AiB0&sig=5c8ikDlPh13i1wEhxu-FC6P-dRA
borg Scale 10	This metric measures the Human perceived feedback by the borg scale quantitative implementation. It is a 0-10 point scale where 0 represents no discomfort and 10 represents agonizing. The scale represents the increased level of discomfort as we move from 0 towards 10.

Benchmarking scenarios available for humanoids

Please, consider that the EUROBENCH framework is in constant evolution over time. The information included in this document has to be taken as a preliminary description of the scenarios, in order to allow participants to FSTP-2 Open Call to select them during proposal preparation.

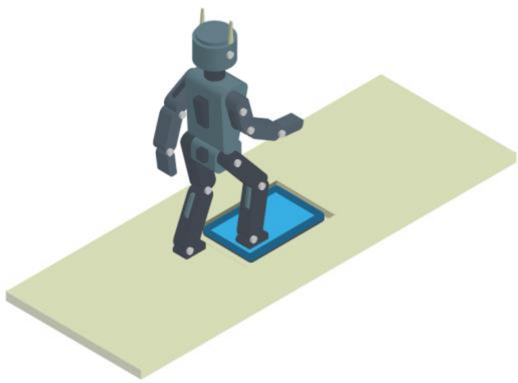
Walking on flat ground

Developed by EUROBENCH

Definition: Humanoid is walking on a flat surface without external perturbation.

TESTBED

Description: Flat ground with force plate embedded in the floor.
Figure:



Equipment:
30 meter track
Force Plate
F/T Sensors of Robot

PROTOCOLS

Protocol's name	Minutes per run	Description
6-MWT	6	Six minute walking test with turning at the end of a 30m track at different velocities

PERFORMANCE INDICATORS (PIs)

Name	Description
Execution time	Time it takes to execute the trajectory

Tracking error	Tracking error from the planned trajectory
F/T error	Error of robotic F/T sensors vs. force plate
Robot dynamics	Forces acting on the robot mechanism
Mechanical energy	Energy consumed normalized over trajectory and execution time
Cost of transport	Mechanical cost of transport
Human likeness	Spatio-temporal comparison of kinematic indicators

Pushing a shopping trolley or walker

Subproject: ***BEAST***

Definition*:* The robot under test has to precisely and safely follow a trajectory through an irregular environment while pushing a shopping trolley/walker. In its trolley version, the protocol evaluates the capability of the robot to safely and accurately operate a self-supporting wheeled transport device (the trolley) while performing navigation tasks.In its walker version, aimed at scenarios where the main difficulty lies in the walking process itself, the protocol evaluates the capability of the robot to minimise its reliance on an external stability-supporting device (the walker).

TESTBED

Description: A test environment is provided with passive structural elements. The robot must follow a trajectory passing through this environment with an instrumented shopping trolley and/or an instrumented walker.

Equipment:

- **Sensors**
    - Laser range scanner: Slamtec RPlidar A3 (https://www.slamtec.com/en/Lidar/A3/)
    - Sensorized handles (force sensors)
- **Actuators**
    - Motorized wheels and differential drive

PROTOCOLS

Protocol name	Minutes per run	Description
Pushing shopping trolley/walker	10	Push a shopping trolley/walker through the environment along a prescribed trajectory, compensating for possible disturbances to its motion.

PERFORMANCE INDICATORS (PIs)

Name	Description

Overall execution time	Overall duration of benchmark execution.
Time to handle	Time elapsed from the start of the benchmark to the first time the handle is touched by the robot/humanoid. This PI accounts for the time the robot takes to perceive the walker/trolley's handle, plan its actions and grasp the handle.
Straight time	Time elapsed on the straight segment.
Slalom time	Time elapsed on the slalom segments.
Straight control accuracy	Measurement of the accuracy of controlling the walker/trolley by the humanoid based on the trajectory of the walker/trolley on the straight segment.
Safety of navigation	Measurement of the safety of the navigation. It is obtained as the minimum distance of the walker/trolley from the obstacles.
Capability level	Number of steps of the benchmark actually completed by the robot. Each step is considered "completed" only after all the steps preceding it have been completed as well.

Sit-to-Stand, Stand-to-Sit

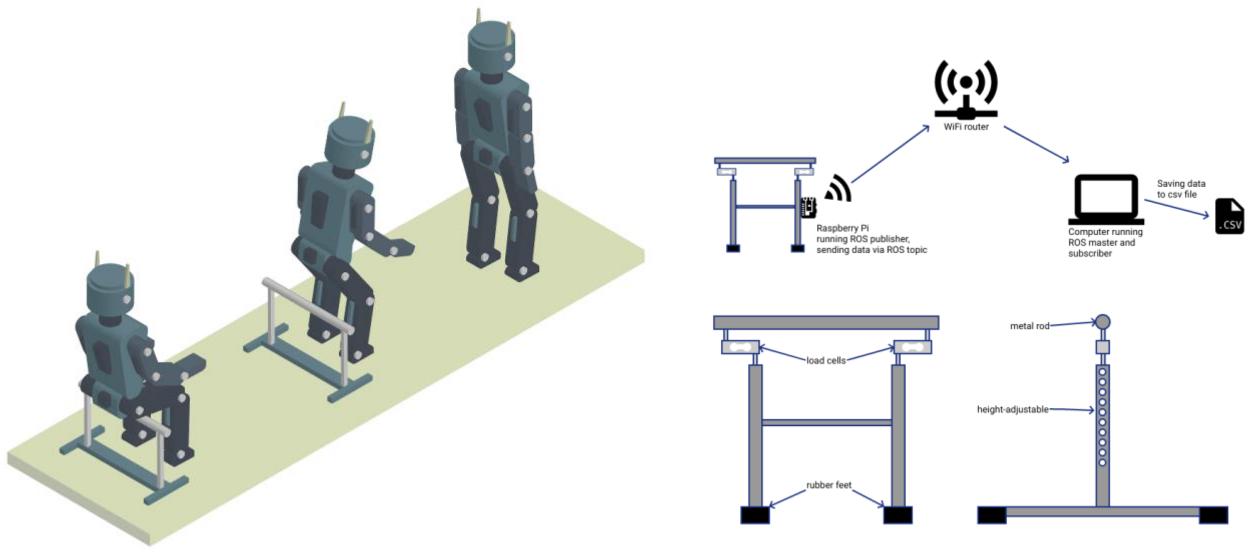
Developed by EUROBENCH

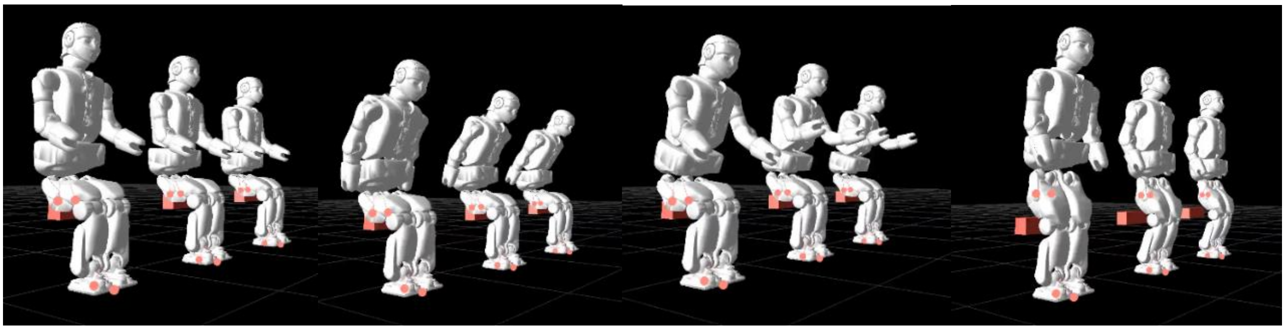
Definition*:* The robot should sit down on an instrumented chair and get up again.

TESTBED

Description: An instrumented chair without armrests using load cells to measure the force acting on the contact point of the chair is provided. For a precise contact point we use a cylinder-shaped seating surface.

Figure:





Equipment:

- Instrumented chair
- Force plate

PROTOCOLS		
Protocol's name	**Minutes per run**	**Description**
Sitting down	-	The robot sits down onto a chair. The height of the chair is calculated based on the leg length and contact point of the robot.
Standing up	-	The robot stands up from a chair. The height of the chair is calculated based on the leg length and contact point of the robot.
STS-Transition	-	The robot sits down and gets up in the shortest possible execution time.

PERFORMANCE INDICATORS (PIs)	
Name	**Description**
Execution time	Time it takes to execute the trajectory
Success rate	Amount of successful repetitions per protocol
Tracking error	Tracking error from the planned trajectory
Robot dynamics	Forces acting on the robot mechanism
Mechanical energy	Energy consumed normalized over trajectory and execution time
Cost of transport	Mechanical cost of transport
Human likeness	Spatio-temporal comparison of kinematic indicators

Standing on a moving surface

Subproject: ***COMTEST***

Definition: The humanoid is standing on a moving platform and instructed to stand upright. The platform moves and provides a stimulus. The body sway is recorded and analyzed.

TESTBED

Description: Posture control and balance under perturbed conditions for the quantification of balancing skills.

Figure:

Equipment:

- **Sensors**
  - IMUs
- **Actuators**
  - Actuated moving platform.

PROTOCOLS

Protocol's name	Minutes per run	Description
Transient Test	15	The humanoid is standing on a moving platform and instructed to stand upright. The platform moves with a *raised cosine* profile. The body sway is recorded and analyzed in the way that is similar to the transient analysis performed with a step function as input profile.
Response characterization	15	Response characterization on the basis of frequency response functions (FRFs) using the Pseudorandom Ternary Sequence Stimulus, PRTS.

PERFORMANCE INDICATORS (PIs)

Name	Description
RC_transient	A support surface movement, e.g. translation or tilt, with a velocity profile of a raised cosine represents a smooth version of a step function that can be used safely for humanoids. In this way the transient response to external stimuli can be evaluated in terms of characteristics like rise time overshoot, settling time, peak time and delay-time.

PRTS_steady	The profile used for the stimulus is a pseudorandom ternary signal, PRTS. A frequency response function shows how the stimulus affects the body sway. Different robots/conditions can be compared frequency-by-frequency or considering the whole "energy" of the body sway.
Human_likeliness	A measure of distance from a human reference, larger numbers are less human-like.

Walking/Standing during pushes

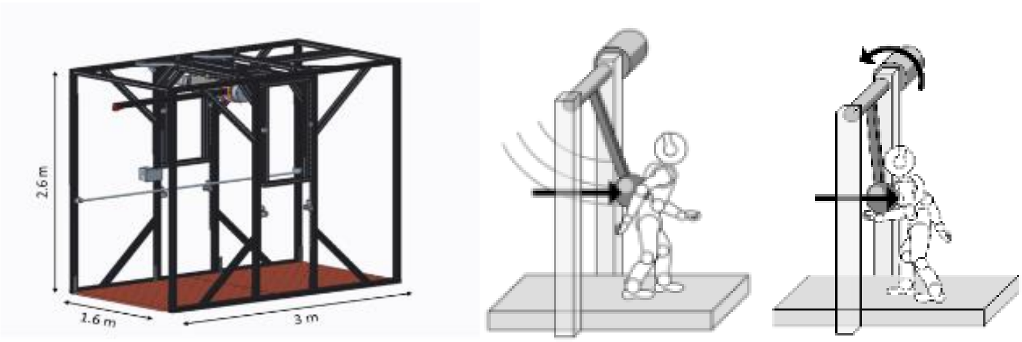
Subproject: ***DYSTURBANCE***

Definition: Legged robots during standing or locomotion tasks must be capable of reacting safely and reject external disturbances. This testbed has the purpose to fully characterize their stability and control behaviors against dynamic loads.

TESTBED

Description: Instrumented actuated pendulum that can be combined with a treadmill to push the robot in dynamic tasks. The system applies different types of replicable disturbance actions on an agent. Capability to provide controlled pushes is required to analyze the system stability properties, and the control reaction.

Figure:



Equipment:

- **Sensors**
  - Motion capture system
- **Actuators**
  - Actuated pendulum

PROTOCOLS

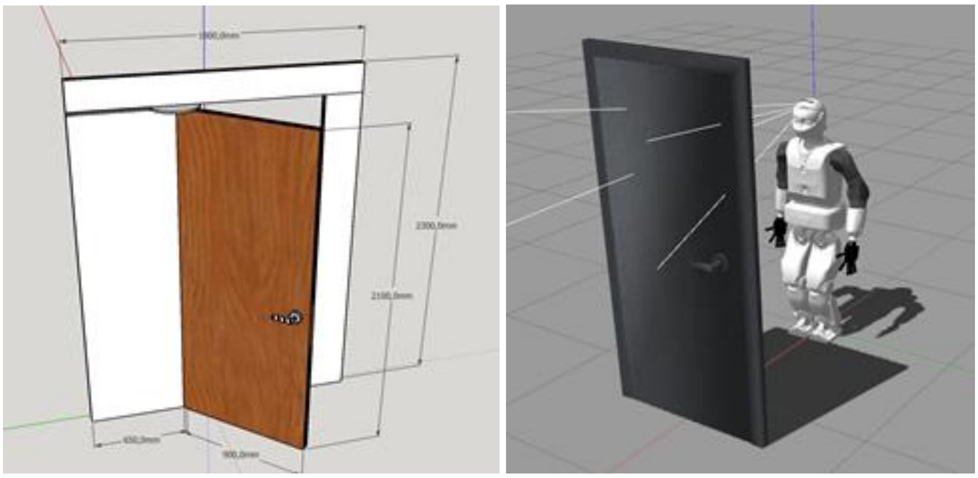
Protocol's name	Minutes per run	Description
Reaction to impulsive disturbance	2	This test characterizes the system stability when subjected to external impacts. The purpose is to define the maximum of impulsive force and energy that the system is capable of handling without incurring in unstability. During the tests, the pendulum falls down freely from a given height, corresponding to a given energy, and hits the agent.
Reaction to sinusoidal force disturbance	5	This test characterizes the system stability in the frequency domain. During the test, the system is subjected to repetitive sinusoidal force disturbances at a given frequency.

Reaction to sinusoidal displacement disturbance	1	This test characterizes the system stability in the frequency domain. During the test, the system is subjected to repetitive sinusoidal displacement disturbances at a given frequency.
Reaction to external quasistatic disturbance	5	This test evaluates the capability of the system to adapt and resist an almost constant push, and to find the maximum value of quasi-static load the system is capable of resisting without falling. We provide a Time-Linear quasi-static Force/Displacement perturbation.

PERFORMANCE INDICATORS (PIs)	
Name	**Description**
Impulsive load stability margin amplitude	Maximum Amplitude of the Disturbance that the agent can withstand without falling. During the run's repetition with the same conditions, it is considered that the control fails if it happens at least 30% of the total runs.
Quasistatic load stability margin amplitude	Maximum Amplitude of the Force Disturbance that the agent can withstand without falling. The test is considered concluded when the robot fails.
Quasistatic displacement stability margin amplitude	Maximum Amplitude of the Displacement Disturbance that the agent can withstand without falling. The test is considered concluded when the robot fails.
Load stability margin amplitude at given frequencies	Maximum Force Amplitude of the Disturbance that the agent can withstand without falling at different frequencies.
Displacement stability margin amplitude at given frequencies	Maximum Displacement Amplitude of the Disturbance that the agent can withstand without falling at different frequencies.
Absorbed energy	The portion of the pendulum energy absorbed by the agent during the impact.
Impulse response function	The agent displacement as function of a given external load. We measure the displacement of the CoM of the agent when subjected to an impulsive external load.

Opening/Closing doors	**Subproject:** ***MADROB***
Definition: Evaluates the capability of the robot to correctly operate standard (hinged) doors for human use. Since doors are ubiquitous in human environments, possessing this capability is crucial for an autonomous robot.	
TESTBED	
Description: Testbed with data acquisition and mechanical action capabilities. Its key element is an active door which, while maintaining all the features of a standard manually-operated hinged door, enables quantitative characterisation of the capability of a robot to interact with it by precisely measuring the forces applied by the robot and the movement of the door. The active door can also apply controlled torque to the door panel to manipulate its physical characteristics as perceived by the robot (e.g. moment of inertia, friction) or to introduce controlled disturbances in its motion (simulating obstructions, effect of wind, push by another user). The testbed is modular: all of its elements are configurable either by physically exchanging them (door type and	

material, handle) or by configuring the actuation system (e.g., to simulate spring action)
Figure:



Equipment:

- **Sensors**
  - Proximity sensors
  - Force sensors in handles
  - Encoder at the door
- **Actuators**
  - Electrical motor at the door

PROTOCOLS		
Protocol's name	**Minutes per run**	**Description**
Walking through door	10	Use a door, initially closed, to reach a new area, then close the door again

PERFORMANCE INDICATORS (PIs)	
Name	**Description**
Execution time	Overall duration of benchmark execution. This timing is affected by human factors since the robot and the benchmark must be manually started at the same time.
Time to handle	Time elapsed from the start of the benchmark to the first time the handle is touched by the robot/humanoid. This PI accounts for the time the robot takes to perceive the door, plan its actions and start opening the door.
Door occupation time	Time elapsed between the humanoid approaching the door from the starting side and the humanoid leaving the destination side (measured by sensors detecting when the humanoid is present in the proximity of the door on each side).
Passage time	Time elapsed between the humanoid starts opening the door (touching the handle) and the humanoid closes the door after reaching the destination side.
Unsafety of door operation	This PI is a measurement of the safety of door operation by the robot based on the maximum angular acceleration of the door panel.
Smoothness of door actuation	This PI is a measurement of the smoothness of the actuation of the door panel based on its angular acceleration.

Roughness of actuation	This PI measures how rough the robot is in operating the door based on the maximum force applied to the handle.
Capability level	Number of steps of the benchmark actually completed by the robot. Each step is considered "completed" only after all the steps preceding it have been completed as well.

Ascending/Descending stairs

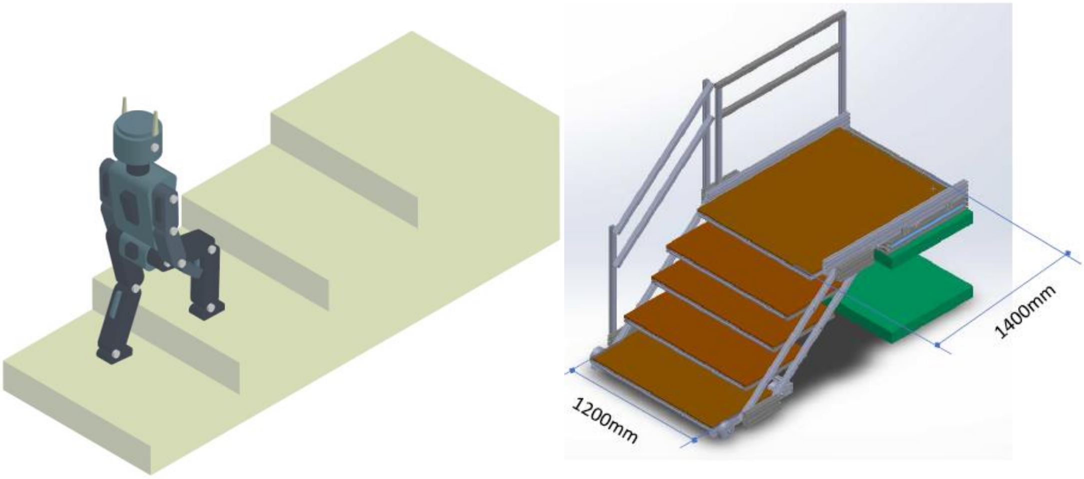
Designed by EUROBENCH

Definition*:* Walking across a given amount of consecutive ascending and descending steps with different step heights.

TESTBED

Description: Height varying stair testbed with four steps and bottom and top platform attached to a lifting table

Figure:



Equipment:
Height adjustable stairs
Force plate

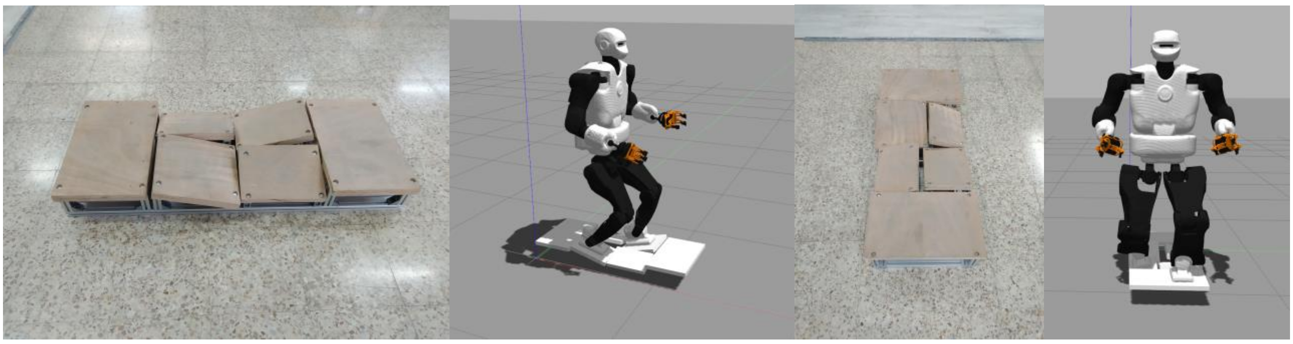
PROTOCOLS

Protocol's name	Minutes per run	Description
Standardized steps up/down	-	The robot performs one run for a standardized step height.
Endurance steps up/down	15	The robot performs several runs for a certain amount of time and a standardized step height.
Maximum step up/down	-	The robot performs several runs. The step height is changed between the runs. The test is finished if the robot cannot climb the current step height or if the maximum available step height is reached.

Fast steps up/down	-	The robot performs several runs at a desired velocity. The step height is changed between the runs. The test is finished if the maximum step height is reached or the robot cannot walk at the current step height at a certain velocity.
Varying steps up	-	The robot performs one run on a stair composed of steps with different heights.

PERFORMANCE INDICATORS (PIs)	
Name	**Description**
Height up/down	Step height that the robot can walk up/down
Variation up/down	Variation in step height between two sequential steps that the robot can walk up
Endurance up/down	Maximum amount of successive stairs the robot can walk up
Success rate	Amount of successful repetitions per protocol
Execution time	Time it takes to execute the trajectory
Tracking error	Tracking error from the planned trajectory
Robot dynamics	Forces acting on the robot mechanism especially the knee joint
Mechanical energy	Energy consumed normalized over trajectory and execution time
Cost of transport	Mechanical cost of transport
Human likeness	Spatio-temporal comparison of kinematic indicators

Walking over irregular terrains	**Designed by EUROBENCH**
Definition:The robot must cross the platform from one side to the other while the robot is stepping over the different oriented platforms, while maintaining a safe walking trajectory.	
TESTBED	
Description: Four different step positions between a start- and end-platform. **Figure:**	



Equipment:
Irregular terrain

PROTOCOLS

Protocol's name	Minutes per run	Description
Open trial	-	The robot crosses the platform
Fixed velocity	-	The robot crosses the platform at a certain velocity
Endurance	15	The robot crosses the platform for a certain amount of time

PERFORMANCE INDICATORS (PIs)

Name	Description
Execution time	Time it takes to execute the trajectory
Max. repetitions	Maximum amount of successive crossings
Success rate	Amount of successful repetitions per protocol
Tracking error	Tracking error from the planned trajectory
Robot dynamics	Forces acting on the robot mechanism
Mechanical energy	Energy consumed normalized over trajectory and execution time
Cost of transport	Mechanical cost of transport
Human likeness	Spatio-temporal comparison of kinematic indicators

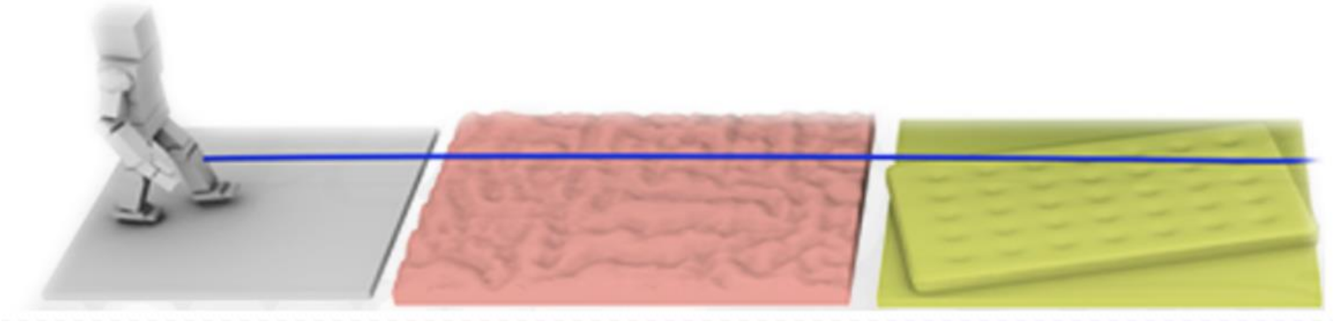
# Walking over soft terrains	**Developed by EUROBENCH**

Definition:The robot walks over different soft terrains.

TESTBED

Description: The material for soft terrains has various different damping.

Figure:



Equipment:
Various soft terrains with clearly defined spring constants

PROTOCOLS

Protocol's name	Minutes per run	Description
Standardized Softness	-	The robot walks over a standardized soft material.
Max. damping	-	The robot performs several runs walking over different soft terrains. The test ends if the robot can walk over all available soft materials or if it cannot overcome the current level of damping.
	-	The robot performs several runs walking over different soft terrains at a certain velocity. The test ends if the robot can walk over all available soft materials or if it cannot overcome the current level of damping at the desired velocity.

PERFORMANCE INDICATORS (PIs)

Name	Description
Max. softness	Softness of terrain (N/mm)
Execution time	Time it takes to execute the trajectory
Success rate	Amount of successful repetitions per protocol

Tracking error	Tracking error from the planned trajectory
Robot dynamics	Forces acting on the robot mechanism
Mechanical energy	Energy consumed normalized over trajectory and execution time
Cost of transport	Mechanical cost of transport

Overcoming obstacles		**Developed by EUROBENCH**
Definition:The robot walks on flat ground stepping over a given set of obstacles with different heights and widths.		
TESTBED		
Description: Testbed consists of various objects of different width and height which can be combined to different configurations		
Equipment: Obstacle testbed		
PROTOCOLS		
Protocol's name	**Minutes per run**	**Description**
Standardized shape	-	The robot steps over one object of a certain height and width.
Various shapes	-	The robot steps over a certain amount of objects with different heights and widths.
Desired velocity	-	The robot steps over a certain amount of different objects with different heights and widths at a certain velocity.
PERFORMANCE INDICATORS (PIs)		
Name	**Description**	
Max. height	maximum height of an obstacle the robot can walk over	
Max. width	maximum width of an obstacle the robot can walk over	
Execution time	Time it takes to execute the trajectory	

Max. repetitions	Maximum amount of successive crossings
Success rate	Amount of successful repetitions per protocol
Tracking error	Tracking error from the planned trajectory
Robot dynamics	Forces acting on the robot mechanism
Mechanical energy	Energy consumed normalized over trajectory and execution time
Cost of transport	Mechanical cost of transport
Human likeness	Spatio-temporal comparison of kinematic indicators

Standing during manipulation

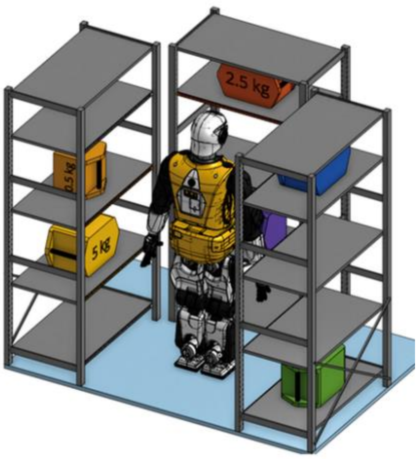
Designed by EUROBENCH

Definition: The robot must maintain balance while picking and placing different objects. All objects protocols will be tested with and without markers on the object to better assess perception.

TESTBED

Description: Ikea with shelves at different heights and positions

Figure:



Equipment:
Color coded shelves + coded targets
Boxes with different weights and shapes

PROTOCOLS

Protocol's name	Minutes per run	Description
Place-in-Box	10	The robot picks a certain amount of objects and places them in a correct box according to the color or shape of the object. The boxes are of different heights and widths. The objects are of different heights and widths, with the same weight.
Place-on-shelf	10	The robot picks a certain amount of objects and places them on the correct shelf. Shelfs are at a different height. The objects are of different heights and widths, with the same weight.
Max. weight and height	-	The robot picks a certain amount of objects and places them on a shelf at a height of 180cm. The objects are of the same size but with increasing weights.

PERFORMANCE INDICATORS (PIs)

Name	Description
Success rate	Amount of correctly placed objects
Average time	Average time until an object has been placed correctly.
Max. weight	Maximum weight of an object the robot can pick
Max. height	Maximum height where object can be placed
Object shape	Maximum height, width, depth of an object the robot can pick.

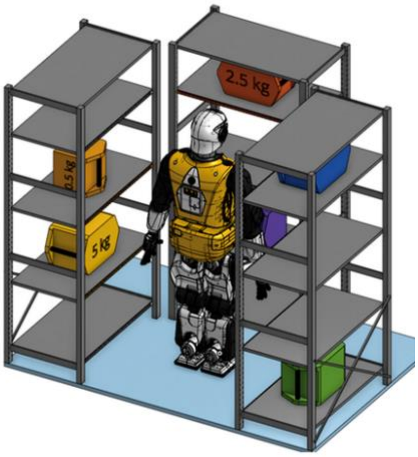
Picking and carrying objects

Developed by EUROBENCH

Definition: The robot maintains balance when picking up and carrying an object at a certain distance. The test is finished if the robot has carried all objects or can't overcome the weight of the current object. The test is repeated with and without markers on the objects to better assess the robot's perception.

TESTBED

Description: Objects from the pick and place testbed will be used
Figure:



Equipment: Different objects of different color and weight

PROTOCOLS		
Protocol's name	**Minutes per run**	**Description**
Basic carrying	-	The robot picks up and carries a specific object of certain weight at a certain distance. The test is finished if the robot has carried the object or cannot overcome the weight of the object.
Increasing weight carrying	-	The robot picks up and carries different objects of increasing weights at a certain distance. The test is finished if the robot has carried all objects or cannot overcome the weight of the current object.
Increasing weight at given velocity	-	The robot picks up and carries different objects of increasing weights at a certain distance at different (increasing) desired velocities. The test is finished if the robot has carried all objects or cannot overcome the weight of the current object at the desired velocity.
Endurance carrying	15	The robot picks up and carries a specific object of a certain weight at a desired velocity for a certain amount of minutes. The test is finished if the robot cannot walk any further or the time has passed.

PERFORMANCE INDICATORS (PIs)	
Name	Description
Max. weight	Weight of the object which can be picked up and carried
Picking time	Time until an object has been picked up
Walking with weight	Walking speed while carrying an object

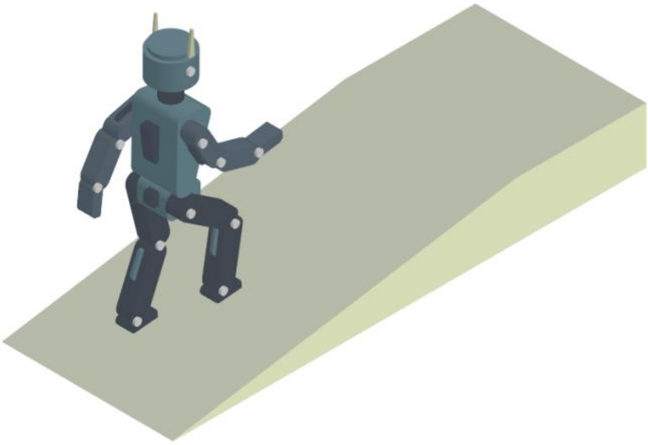
Ascending/Descending slopes	**Designed by EUROBENCH**

Definition: Walking on surfaces that are inclined (uphill and downhill) along the gait direction.

TESTBED

Description: Utilizing the Roll-a-Ramp and a lifting table several slope angles can be created

Figure:



Equipment: F/T Sensors of robot

PROTOCOLS

Protocol's name	Minutes per run	Description
Basic slope walking up/down	-	The robot performs one run for a certain standardized slope angle.
Max. angle up/down	-	The robot performs several runs for a given amount of different slope angles until the maximum slope angle is reached or the robot cannot walk at the current angle.
Max. velocity up/down	-	The robot performs several runs for a given amount of different slope angles at different (increasing) desired velocities until the maximum slope angle is reached or the robot cannot walk at the current angle at a certain velocity.

PERFORMANCE INDICATORS (PIs)

Name	Description
Max. angle up/down	Slope angle the robot can walk up/down

Max. velocity up/down	Maximum velocity the robot can walk up/down at a given slope inclination
Execution time	Time it takes to execute the trajectory
Max. repetitions	Maximum amount of successful successive crossings
Success rate	Amount of successful repetitions per protocol
Tracking error	Tracking error from the planned trajectory
Human likeness	Spatio-temporal comparison of kinematic indicators
Robot dynamics	Forces acting on the robot mechanism
Mechanical energy	Energy consumed normalized over trajectory and execution time

Walking on a treadmill

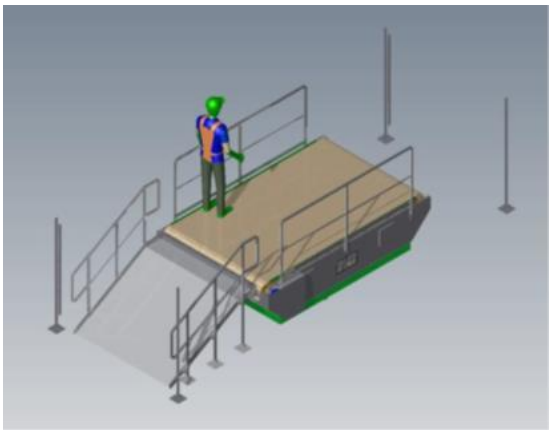
Developed by EUROBENCH and the TREADMILL subproject

Definition: Treadmill is for the locomotion and balancing trials as well the execution of long time endurance tests under variable speed and inclination settings.

TESTBED

Description: The testbed is for a long time walking test on the treadmill under uniform condition (e.g. constant speed and inclination) to quantify the endurance, speed, and energy efficiency of the walking robot.

Figure:



Equipment:

- **Sensors**
  - Encoders in the testbed
- **Actuators**
  - Geared motors in the testbed

PROTOCOLS

Protocol's name	Minutes per run	Description
Long time walking on level ground	10 min	Walking on the treadmill with zero slopes. Walking speed is predetermined before the test execution and it is constant during the test.
Long time walking on a slope with pitch angle	10 min	Walking on the treadmill with a slope (pitch angle 10 deg). Walking speed is predetermined before the test execution and it is constant during the test.
Long time walking on a slope with roll angle	10 min	Walking on the treadmill with a slope (roll angle 5 deg). Walking speed is predetermined before the test execution and it is constant during the test.

PERFORMANCE INDICATORS (PIs)	
Name	**Description**
Normalized walking speed	Walking speed normalized by leg length of the robot. It describes how fast steady-state walking can be operated.
Normalized total walking distance	Total walking distance normalized by leg length of the robot. It describes how far the steady-state walking can be operated.
Normalized energy efficiency	Consumed energy per normalized distance. In addition, it is normalized by the weight of the robot. This represents the energy efficiency of the robot walking.
Walking control system efficiency	Consumed energy per normalized distance of the robot hardware and control system. It represents the energy efficiency of the robot hardware and the controller.

Walking on laterally inclined surfaces	Developed by EUROBENCH

Definition: Testbed for walking through the laterally inclined terrains.

TESTBED

Description: The testbed is composed of reconfigurable blocks that can set flat or inclined terrains for flexible walking test scenarios.

Figure:

Equipment: To be determined.

PROTOCOLS		
Protocol's name	**Minutes per run**	**Description**
Walking on inclined terrain	15 min	Walking on three different sets of terrains with laterally inclined surfaces. Each terrain set has a different angle.

PERFORMANCE INDICATORS (PIs)	
Name	**Description**
Normalized walking distance	The total walking distance the robot successfully walks. It is normalized by the leg length of the robot.
Normalized walking speed	The average walking speed calculated by dividing the normalized walking distance by the execution time for the test.
Difficulty level	The difficulty level of the terrains where the robot successfully walks. It is calculated by the ratio between the angle of the slope and the leg length of the robot.

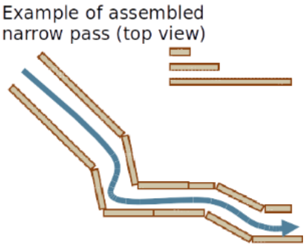
Moving in narrow spaces

Developed by EUROBENCH

Definition: Testbed for walking through the narrow space configured by reconfigurable and movable walls.

TESTBED

Description: The testbed is composed of reconfigurable walls that can set narrow space for robot walking test scenarios.
Figure:



Equipment: To be determined.

PROTOCOLS		
Protocol's name	**Minutes per run**	**Description**

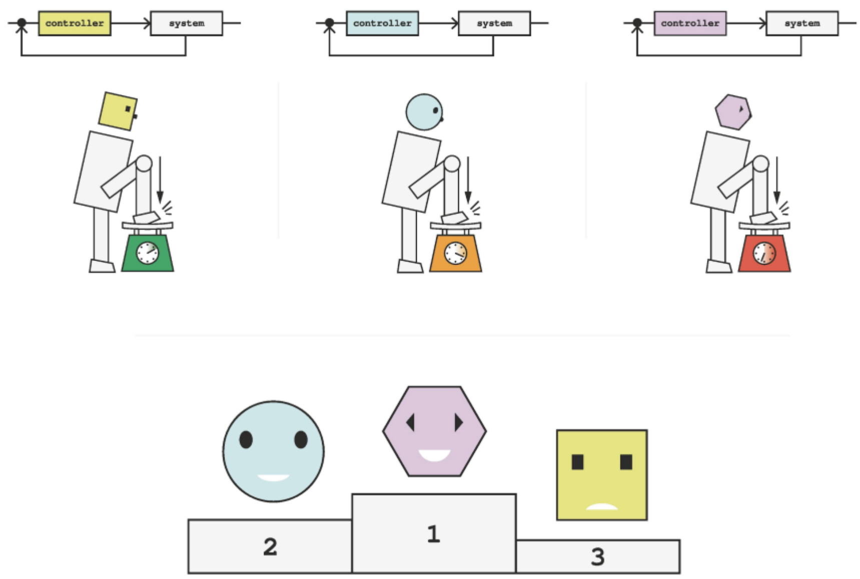
Walking through narrow space	30 min	Walking through three different sets of course with narrow space.

PERFORMANCE INDICATORS (PIs)	
Name	**Description**
Normalized Walking distance	The total walking distance the robot successfully walks. It is normalized by the leg length of the robot.
Normalized walking speed	The average walking speed calculated by dividing the normalized walking distance by the execution time for the test.
Narrowness level	The narrowness of the space that the robot successfully walks. It is calculated by the ratio of the width of the narrow space to the shoulder width of the robot.

Other available equipment

This section includes two additional devices (a motion capture system and a testbed for actuation characterization) that can be used independently from the scenarios above described.

Force control characterization	**Subproject: FORECAST**
Definition: Controlling the interaction force between a robot and several kinds of environments: The force control algorithm to benchmark is implemented in simulation and tested experimentally considering a specific actuation system and a predefined set of environments. The actuation system is defined in terms of motor inertia, friction and series stiffness while the set of environments are defined by a set of inertia, and stiffness values (environments are assumed critically damped). Sweep signals with user-defined maximum frequency and amplitude are used as force reference (to characterize force tracking) and velocity disturbance (to characterize transparency).	
TESTBED	
Description: The testbed will be composed of a software package to validate force control algorithms by means of simulations and two physical testbenches to validate the simulation results and to provide a standardized experimental hardware and software platform for force control experimentation. **Figure:**	



Equipment:

- **Sensors**
  - Encoders
  - Torque sensors
- **Actuators**
  - **Geared motor**
  - **Direct drive motor**

PROTOCOLS

Protocol's name	**Minutes per run**	**Description**
Force control simulations	10	Simulate the behaviour of a force control algorithm on a single (simulated) hardware and on multiple environments.
Force control testbed	10	This protocol experimentally measures the behaviour of a given force control algorithms and a given actuator in different environmental conditions

PERFORMANCE INDICATORS (PIs)

Name	**Description**
static_error	The static error between the reference signal and the output of the system.
dynamic_error	The dynamic error is the error between the reference signal and the output of the system not considering the static error.
worst_case_environments	It corresponds to the types of environments in which the system works worst.
best_case_environments	It corresponds to the types of environments in which the system works well.

overshoot_level	It's the maximum overshoot of the system response, in percentage.
bandwidth	It represents the bandwidth that the system can hold in the different environments taken into consideration.
linearity	It represents if the system is a linear one or not. A value equal to 1 means that the system is linear.

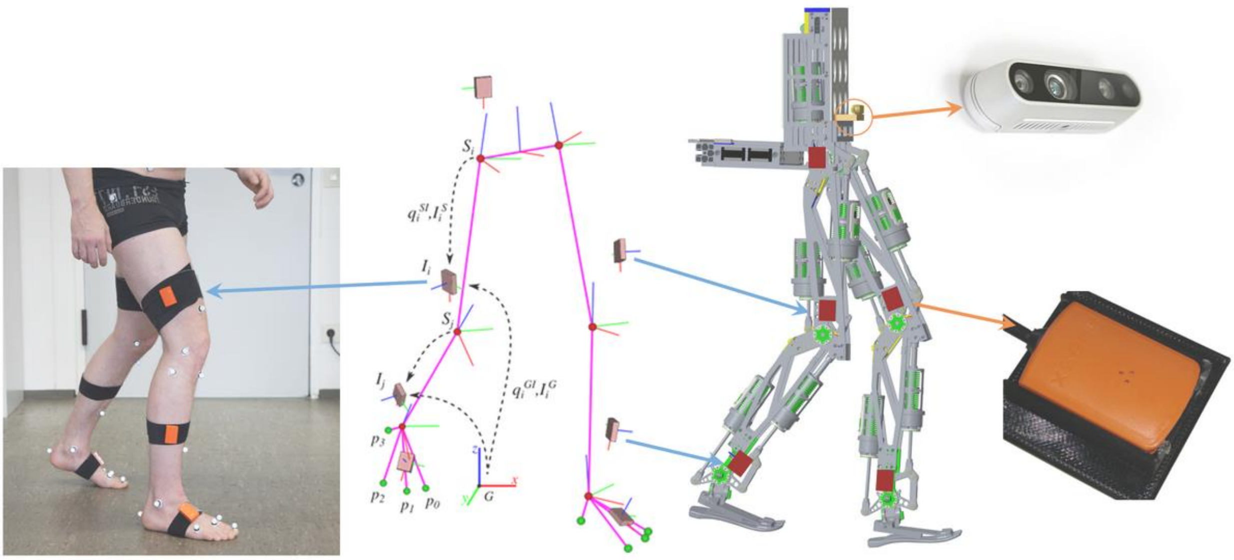
Inertial sensors	**Subproject: IMCVO**

Definition: Wearable sensory system, based on inertial motion capture device and visual odometry that can easily be mounted on a robot, as well as on the humans and delivers 3D kinematics in all the environments for validation tests.

TESTBED

Description:
It is planned to use recent advances in inertial measurement units based 3D kinematics estimation that does not use magnetometers and, henceforth, is robust against magnetic interferences induced by the environment or the robot.
This allows a drift-free 3D joint angle estimation of e.g. a lower body configuration or a robotic leg in a body-attached coordinate system.

Figure:



Equipment:
X-Sense
Intel RealSense

PROTOCOLS

Protocol's name	**Minutes per run**	**Description**

Sensor Calibration	1	Calibration run to activate and synchronize wearable sensory system
PERFORMANCE INDICATORS (PIs)		
Name	**Description**	
Step length	Right and left step length mean and SD across N gait stride (scalar values)	
Orientation errors	Error between developed system and optical reference	
Joint angles	Joint Angles of lower body configuration	
Absolute orientation	Absolute orientation w.r.t a fixed coordinate system in space	