BenchBalance

A device to apply well defined perturbations for benchmarking balance capabilities of wearable robots.

Abstract

The present document provides a description of all the sections of the excel sheet that includes protocol/PI/PI Algo. Additional information is reported to detail protocol steps and PIs calculation.

BenchBalance

Beneficiaries involved: *Polytechnic University of Madrid (UPM), Università Campus Bio-Medico di Roma (UCBM), University of Twente (UT)*

Authors: *F. Bentivoglio, N.L. Tagliamonte*

Reviewers: *Edwin van Asseldonk, Eduardo Rocon, Cristina Bayón*

Dissemination level: *Confidential*

Table of contents

1 Introduction

There is a lack of systems intended to objectively assess the features of exoskeleton-assisted balance, especially, if the intention is to quantify balance derived from perturbed conditions. *BenchBalance* project aims at developing a benchmarking solution to conduct reproducible assessments of balance in various conditions, mainly focused on wearable exoskeletons but also applicable to humans not wearing them.

The main objective of *BenchBalance* project is to design and develop a novel and low-cost testbed capable of measuring well-defined external perturbations manually provided by an experimenter, in terms of magnitude, orientation and location, to subjects wearing or not an exoskeleton. To approach this goal, BenchBalance integrates two key elements: (1) a portable perturbator equipped with different sensors, which can provide and quantify the applied perturbations; and (2) a smart garment, which determines the location of the generated disturbance on the human body. The information provided by the developed testbed has to be merged and synchronized with the data provided by the tested wearable exoskeleton and/or by a conventional motion-capture (Mo-Cap) system, and subsequently analysed to assess the balance control of the user-exoskeleton compound system.

The *BenchBalance* benchmarking software (1) collects and merge the data from the perturbator and the smart garment together with kinematic information coming from the exoskeleton and/or the Mo-Cap system, and get them in a format compatible with EUROBENCH testing facility and its database structure; (2) synchronizes all the collected data, which will allow data association and will provide extra information like the possibility of knowing the moment when the perturbations were exerted, (3) derives metrics to assess balance capacities, in terms of body-sway and recovery time.

The current document describes the protocol and all the necessary analysis to extract the suitable performance scores to quantify the balance response to the applied perturbations in static conditions.

2 Scenario and protocol

As requested in Part C – Section 3 of the project Final Report, this section provides details on the excel sheet that includes protocol/PI/PI Algo, i.e. the file `BenchBalance_Protocol_PI_PIalgo_v2.xlsx`.

2.1 Generalities

The project develops a low-cost system that provides a quantitative assessment related to the reaction and capacity of humans assisted by a wearable exoskeleton to respond to controlled external perturbations. To comply with the balance assessment, *BenchBalance* is focused on three key factors: first, it is necessary to quantify the disturbance applied to a human wearing an exoskeleton in terms of force and orientation; second, it is crucial to perform a correct estimation of where the perturbation is applied as strategies might differ depending on the location of such perturbation; and third, it is necessary to derive metrics quantifying the balancing capabilities of the user supported or not by the worn exoskeleton.

The assessment scenario encompasses the required features to perform those experiments in a safe, correct, and reproducible way. Moreover, the subject is tested respect to its balance capabilities and evaluated while wearing or not an active exoskeleton: he/she has to maintain balance reacting to well-defined external perturbations manually provided by an experimenter.

Generally, the standing user receives perturbations from the front, back, right, and left sides of small and large levels of force.

2.2 BenchBalance testbed

Based on the introduced purpose, the developed testbed is composed by:

- *Portable perturbator*: it provides the well-defined disturbance to the user. The perturbator can be easily handled by the operator so the versatility of the device is very high in terms of usability, and wide range of possible perturbations generated. It is equipped with different sensors to quantify the generated disturbance, among which: (1) an inertial sensor to measure the relative orientation of the perturbation with respect to the human, who wears a second inertial sensor integrated in a smart garment described below; and (2) a force sensor that quantifies the force of such perturbation applied to the user.

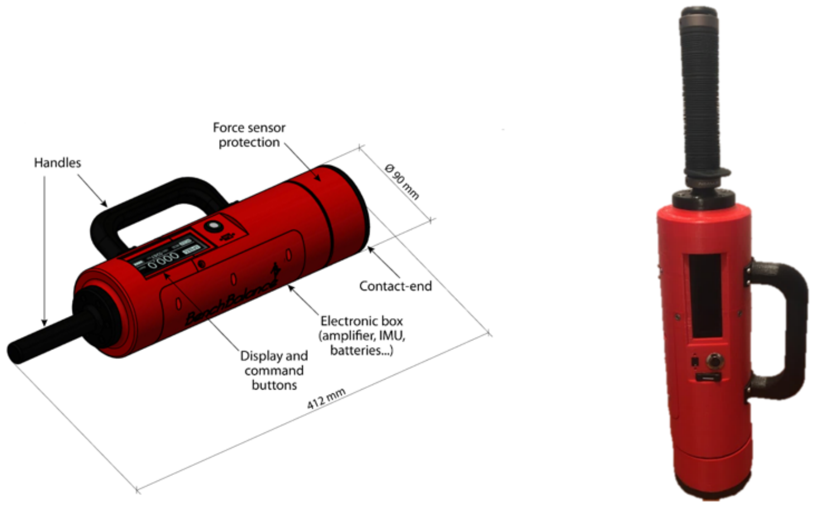

Figure 1 Portable perturbator: CAD design (left), real device (right)

- *Smart garment*: it is a textile equipped with pressure sensors over the user's upper body in order to determine the location of the disturbance generated by the portable perturbator in relation to the human. It is used to detect in which section of the human body the perturbation is applied, and to provide supplementary information about the plane of motion of the perturbation.

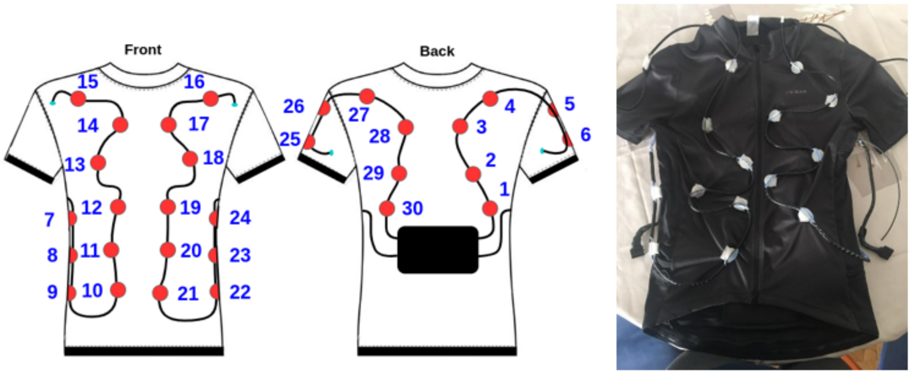

Figure 2 Smart garment: design (left), real system (right)

Schematic pictures of the testbed are reported in Figure 1 and Figure 2.

Further details for both systems can be found in the file `BenchBalance_Manual.doc`, available in the `TESTBED` Documentation folder.

The information provided by the perturbator and by the smart garment are merged and synchronized with the data provided by the wearable exoskeleton or by a conventional Mo-Cap system (if the exoskeleton is not used), and subsequently analysed to assess the balance in terms of body-sway magnitude and time of recovery.

2.3 Controlled variables

In the BenchBalance protocol, controlled variables (CVs) refer to parameters that are needed by the algorithms for computing the performance indicators and represent the experimental conditions evaluated during the tests. Since pushes are provided manually, providing perturbations with certain features of CVs may require some training for the experimenter and multiple trial/error repetitions. CVs include:

1. *Perturbation magnitude*: it is the maximum amplitude of the force applied by the experimenter to the subject by means of the perturbator. In particular, the perturbator is able to monitor force along all the three axes and we calculate the magnitude of the resultant vector.

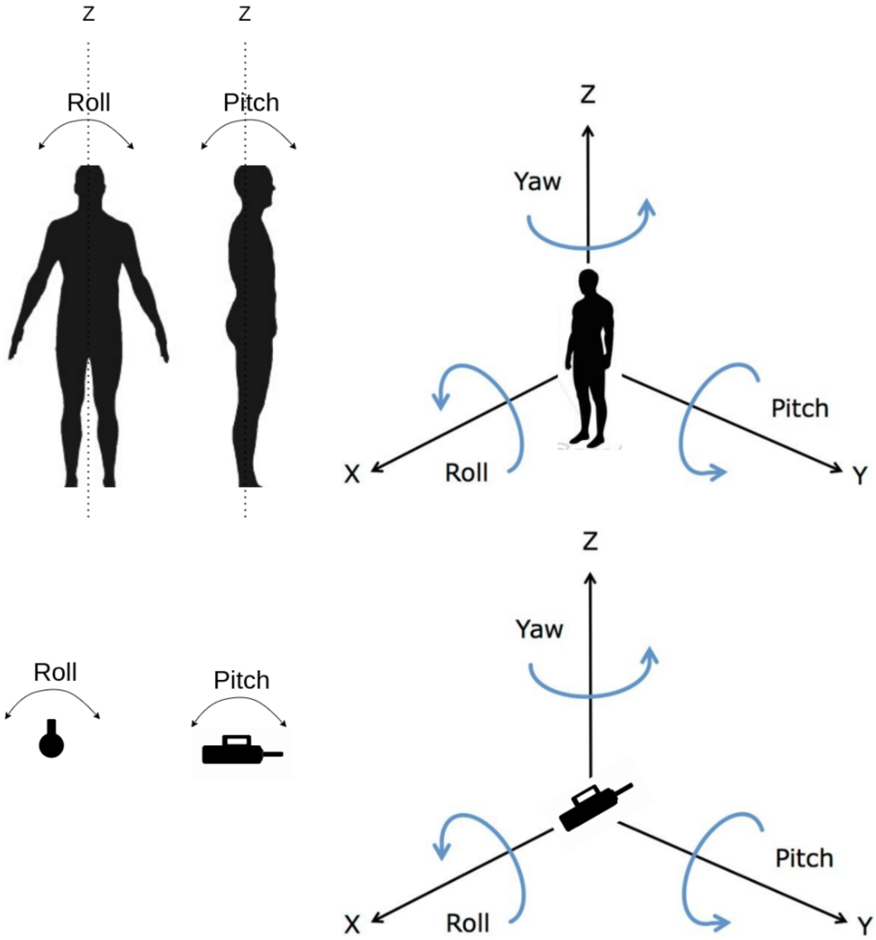

Figure 3 Reference frames for the smart garment on human (up) and the perturbator (down)

Within the protocol, the user is evaluated based on two levels of perturbation magnitude: a small one, computed as 8 ± 2 % of the total mass (considering the weight of the exoskeleton, if present, and the weight of the human body) and a large perturbation, computed as 16 ± 2 % of the total mass.

2. *Perturbation type*: it is a string indicating the level of perturbation provided. The options are: 'small' or 'large'.
3. *Perturbation duration*: it is the time interval in which the force is applied by the experimenter to the subject by means of the perturbator (Figure 4). This is calculated as the elapsed time of the force exceeding a (no force) threshold of 5 N and it is expressed in seconds. For conducting the protocol, an acceptable value of the perturbation duration is 0.3±0.1 s.

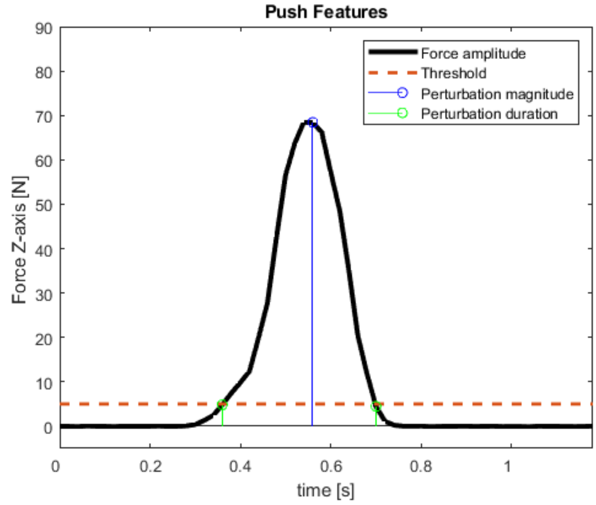

Figure 4. Example of data for the calculation of perturbation magnitude and duration. The threshold is set to 5 N

1. *Perturbation orientation*: it is the relative orientation between the human upper body and the direction of the force applied by the experimenter to the subject by means of the perturbator. It is expressed as pitch, yaw, and roll components in degrees. Figure 3 depicts the reference frames of the smart garment and of the perturbator.

2. *Perturbation location*: it is the position on the subject's upper body where the perturbation is applied by the experimenter by means of the perturbator. It is extracted by checking the number of the most active sensors in the smart garment and identified based on the map reported in Figure 5.

3. *Exoskeleton*: it is boolean value indicating the presence or not of the exoskeleton as follows
    a. 0: without exoskeleton;
    b. 1: with exoskeleton.

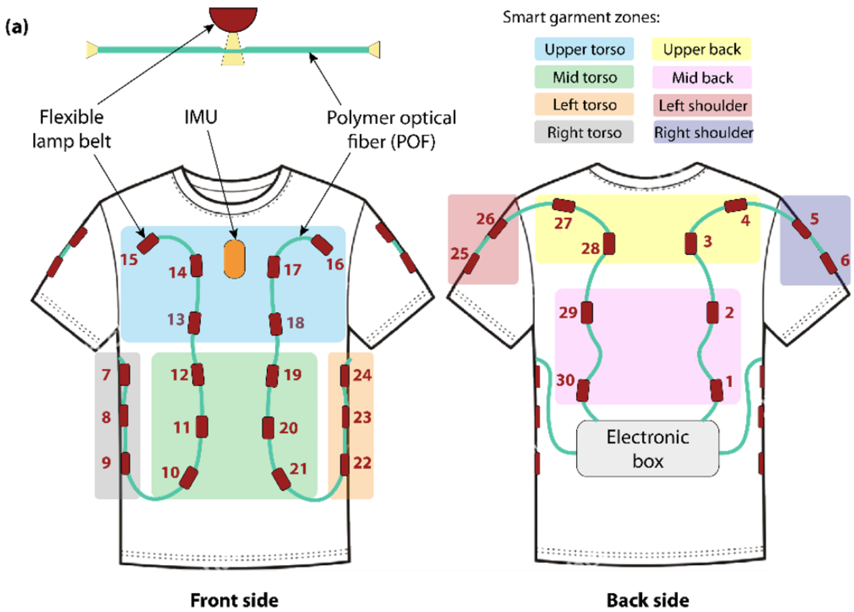

Figure 5 Smart garment zones.

2.4 Protocol steps

To perform the balance test of a user with (or without) an exoskeleton, the next steps should be followed:

1. **Place the smart garment onto the subject body.** The garment has to be worn by the subject.

2. **Place the exoskeleton (if any) onto the subject body.** If an exoskeleton is included in the protocol, it has to be worn in a way that the sensors of the garment could be accessible. If an exoskeleton is used, it should provide the possibility to save joint angles data (hip adduction, hip flexion, knee flexion and ankle dorsiflexion) in the EUROBENCH data format (as recommended in the Plug-in Gait model from Vicon).
3. **Place motion sensors (if any) onto the subject body.** This step is required if the exoskeleton is not able to monitor joint angles data or the balance assessment involves only the subject. An experimenter could use any Motion Capture system, as long as joint angles data are being recorded (hip adduction, hip flexion, knee flexion and ankle dorsiflexion) in the EUROBENCH data format (as recommended on the Plug-in Gait model from Vicon.
4. **Turn on the Smart Garment** (details in `BenchBalance_Manual.doc` and `BenchBalance_Guide_how_to_use.doc` file).
5. **Turn on the Pusher** (details in `BenchBalance_Manual.doc` and `BenchBalance_Guide_how_to_use.doc` file).)
6. **Connect devices** (details in `BenchBalance_Manual.doc` and `BenchBalance_Guide_how_to_use.doc` file).).
   6.1. Open Bluetooth Manager application
   6.2. Right click in Smart Garment and choose “serial port” (SG)
   6.3. Right click in Pusher and choose “serial port” (PU)
7. **Launch the BenchBalance software (read `BenchBalance_Guide_how_to_use.doc`)**
   7.1. Choose the SG port created in step 6.2
   7.2. Choose the PU port created in step 6.3
   7.3. Click the ‘connect’ button
8. **Place the subject in a fixed standing position and launch the Calibration.** The feet distance has to be equal to the shoulder width and for convenience can be indicated by symbols on the ground.
   8.1. Ask the subject to keep standing while the pusher is in the calibration position
   8.2. Press “calibrate” button and wait 5 seconds
   8.3. Calibrate the smart garment (details in `BenchBalance_Manual.doc` file)
9. **Choose perturbation protocol tab.** The experimenter has the option of measuring freely or follow a pre-defined *Full* protocol. The Full protocol is equivalent to a total of 80 perturbations (front-back AND right-left direction; upper AND lower part of the trunk). The recording of this protocol has the advantage of later using the processing of data and performance indicators defined by BenchBalance.
10. **Put the subject in a standing position and start the perturbation protocol.** The subject has to stand with feet at a fixed selected distance equal to his/her shoulder width. This distance has to be indicated on the ground and has to be guarded during the experiment. The subject has to be informed that he will receive perturbations with different intensity and location, and he has to reject them keeping the feet fixed on the ground (i.e. without taking a step or lifting heels). Perturbations are delivered manually by the experimenter, hence providing perturbations with certain features may require some training and multiple trial/error repetitions. The objective is to deliver 5 suitable perturbations of the same desired perturbation and be careful to wait at least 3 seconds between two consecutive pushes.

To this aim the experimenter has to continue providing pushes by checking the software acquisition interface and has to stop until 5 good pushes are actually delivered. Lastly, during the trial the experimenter has to pay attention that between two consecutive pushes the subject will go back to the initial standing position. If the pre-defined protocol is being performed, the user interfaces will guide the experimenter during this protocol.

Location and type of the perturbations considered in the pre-defined *Full* protocol:

10.1. **Location:** Lower back. **Sensors:** 1-2-29-30. **Type:** small
10.2. **Location:** Upper back. **Sensors:** 3-4-27-28. **Type:** small
10.3. **Location:** Lower back. **Sensors:** 1-2-29-30. **Type:** large
10.4. **Location:** Upper back. **Sensors:** 3-4-27-28. **Type:** large
10.5. **Location:** Lower torso. **Sensors:** 10-11-12-19-20-21. **Type:** small
10.6. **Location:** Upper torso. **Sensors:** 13-14-15-16-17-18. **Type:** small
10.7. **Location:** Lower torso. **Sensors:** 10-11-12-19-20-21. **Type:** large
10.8. **Location:** Upper torso. **Sensors:** 13-14-15-16-17-18. **Type:** large
10.9. **Location:** Right side-torso. **Sensors:** 7-8-9. **Type:** small
10.10. **Location:** Right side-shoulder. **Sensors:** 5-6. **Type:** small
10.11. **Location:** Right side-torso. **Sensors:** 7-8-9. **Type:** large
10.12. **Location:** Right side-shoulder. **Sensors:** 5-6. **Type:** large
10.13. **Location:** Left side-torso. **Sensors:** 22-23-24. **Type:** small
10.14. **Location:** Left side-shoulder. **Sensors:** 25-26. **Type:** small
10.15. **Location:** Left side-torso. **Sensors:** 22-23-24. **Type:** large
10.16. **Location:** Left side-shoulder. **Sensors:** 25-26. **Type:** large

11. **Save data and close the interface** (details in `BenchBalance_Manual.doc` and `BenchBalance_Guide_how_to_use.doc` files).

3 Performance Indicators

3.1 PIs definition

BenchBalance protocol calculates two PIs. Each PI includes several additional information regarding the provided perturbation, based on the CVs presented in Sec. 2.3:

- Perturbation magnitude;
- Perturbation duration;
- Perturbation orientation (pitch, yaw);
- Perturbation location.

The BenchBalance PIs are:

1. *pi_bodysway*: it represents the maximum body sway angle in response to a perturbation. A high value of the body sway indicates less ability of the subject in maintaining the balance.

   For antero-posterior perturbations: considering in the sagittal plane the line from the CoM to the ankle joints rotation axis (as reported in Figure 6), the body sway is calculated as the maximum angle between this line at rest and the same line after the perturbation.

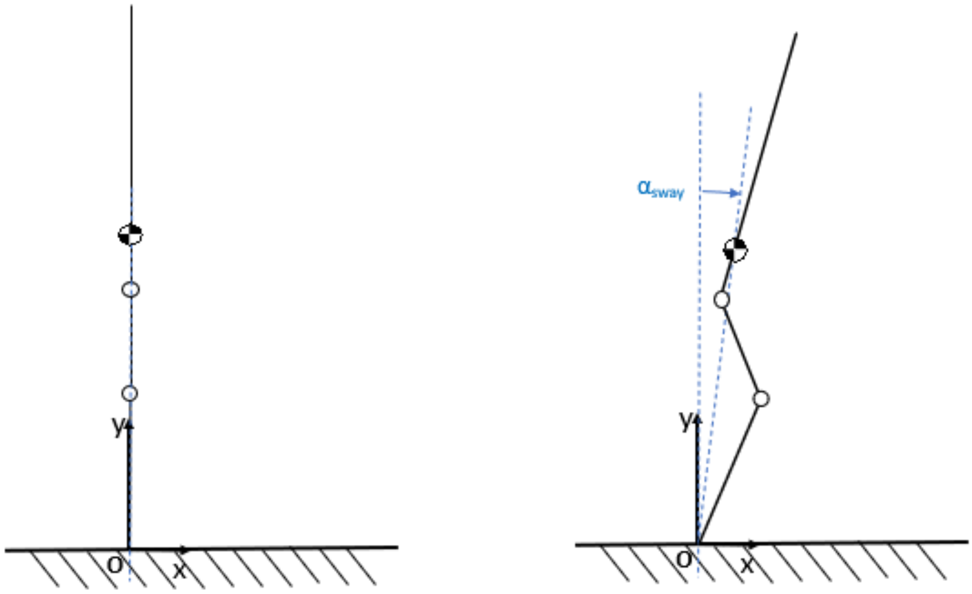

Figure 6. On the left the initial posture of a standing subject, while on the right the body sway angle in response to a perturbation

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 (Figure 7).

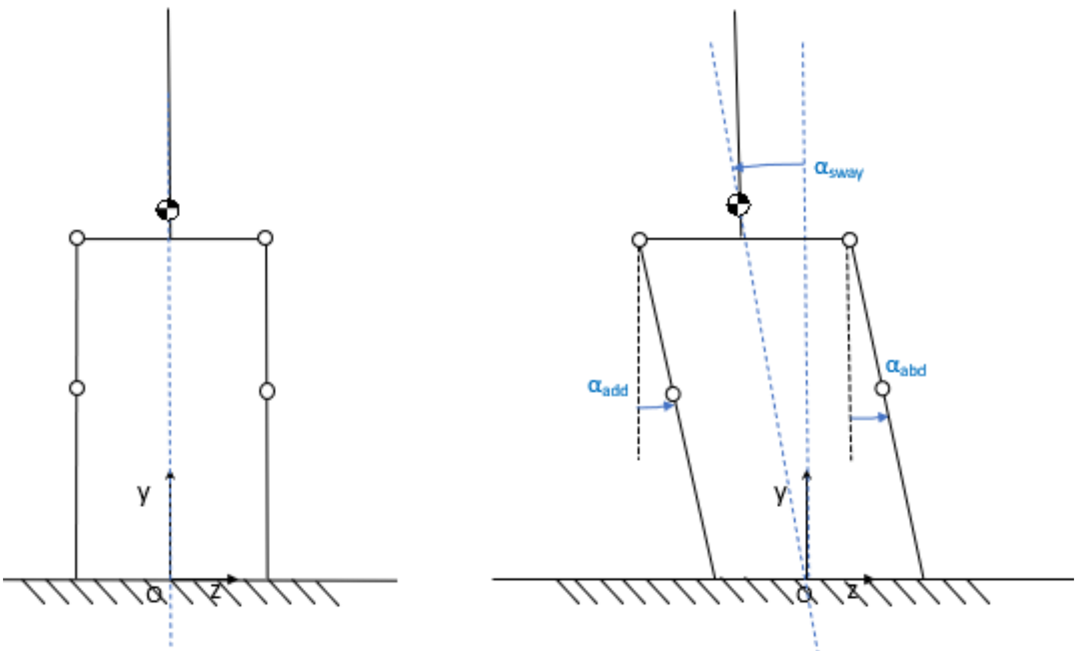

Figure 7. On the left the initial posture of a standing subject, while on the right the body sway angle in response to a perturbation

This PI is stored as a vector with the following structure:

```
type: 'vector'
label: ['perturbation_magnitude', 'perturbation_duration',
'perturbation_orientation_roll',
'perturbation_orientation_pitch', 'perturbation_orientation_yaw',
'perturbation_location', 'body_sway']
value: [value, value, value, value, value, value, value]
```

2. *pi_recoverytime*: it represents the time spent to recover from a perturbation. A high value of the recovery time indicates less ability of the subject in maintaining the balance.
   It 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 of 0.015 rad/s) after the perturbation.
   This PI is stored as a vector with the following structure:

```
type: 'vector'
label: ['perturbation_magnitude', 'perturbation_duration',
'perturbation_orientation_roll',
'perturbation_orientation_pitch', 'perturbation_orientation_yaw',
'perturbation_location', 'recovery_time']
value: [value, value, value, value, value, value, value]
```

3.2 PIs calculation

PIs are calculated by the algorithm `PI_benchbalance.m`.
In order to obtain the PIs, the CoM of the human subject or of the user plus the exoskeleton needs to be computed. The models in the sagittal and frontal plane were considered separately.

We considered a 5-segments rigid body system composed by: left/right shank segment, left/right thigh segments, and the HAT (head, arm and trunk [1]). Human joints were considered as pure rotary joints. The feet were excluded from the model, since during the BenchBalance testes they were supposed to be not moving, i.e. in continues contact with the ground. To this aim, for the sake of simplicity, the ankle joint was considered virtually connected directly with the ground and, as explained in section 3.1, the CoM motion in the sagittal plane was considered as a rotation around the ankle joint.

For the considered segments (thigh, shank and HAT), anthropometric input parameters for the BenchBalance routine are:

1. lengths, to be directly measured on the subject's body;
2. masses, to be computed starting from subject total mass based on [1].

The mass and the CoM of each segment are reported in Table 1.

Table 1. Anthropometric data based on [1].

Segment	Definition (from/to)	Segment weight/total body weight	Center of Mass wrt distal joint
Thigh	Greater trochanter/femoral condyles	0.1000	0.567
Shank	Femoral condyles/medial malleolus	0.0465	0.567
HAT[1] (Head, Arms, and Trunk)	Greater trochanter/glenohumeral joint	0.6780	0.374

For the evaluation of the recovery time, we first computed the body sway velocity by differentiating and low-pass filtering the body sway using a second order Butterworth filter with a cut-off frequency of 10 Hz.

3.2.1 Sagittal plane

In the sagittal plane model the following assumptions were considered (Figure 8):

- left and right leg are considered identical and symmetrically placed;
- only ankle, knee and hip pure flexion/extension angles were considered, derived by comparing the relative orientations of the proximal (parent) and distal (child) segments around each joint:
    - Hip: flexion rotation was calculated about an axis parallel to the pelvic transverse axis which passes through the hip joint centre. The sagittal thigh axis is projected onto the plane perpendicular to the hip flexion axis. Hip flexion is then the angle between the projected sagittal thigh axis and the sagittal pelvic axis. A positive (flexion) angle value corresponds to the situation in which the knee is in front of the body. For details check the Plug-in Gait model from Vicon.
    - Knee: the sagittal shank axis is projected into the plane perpendicular to the knee flexion axis. Knee flexion is the angle in that plane between this projection and the sagittal thigh axis. The sign is such that a positive angle corresponds to a flexed knee.
    - Ankle: the foot vector is projected into the foot sagittal plane. The angle between the foot vector and the sagittal axis of the shank is the foot dorsi/plantar flexion. A positive value corresponds to dorsiflexion.

[1] The HAT segment corresponds to the back segment (namely 'full back') of the Human Model described in the EUROBENCH data format.

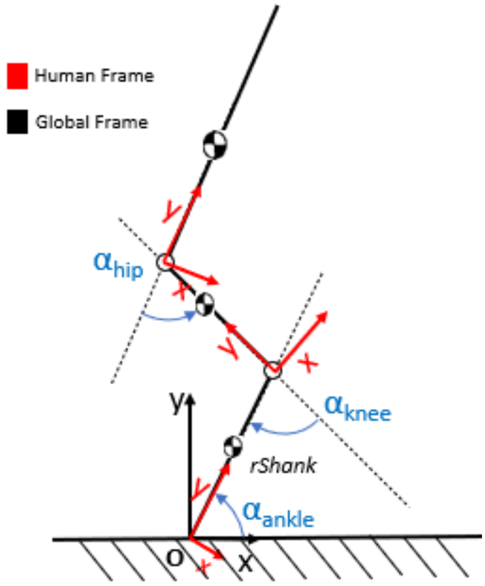

Figure 8. Model conventions in sagittal plane

3.2.2 Frontal Plane

In the frontal plane the following approximations were considered (Figure 9):

- The hip add/abduction angle was considered equal for the left/right hip joints.
- The HAT segment underwent only translation movements, parallel to the ground.

Hip adduction is measured in the plane of the hip flexion axis and the knee joint centre. The angle is calculated between the long axis of the thigh and the frontal axis of the pelvis projected into this plane. A positive number corresponds to an adducted leg.

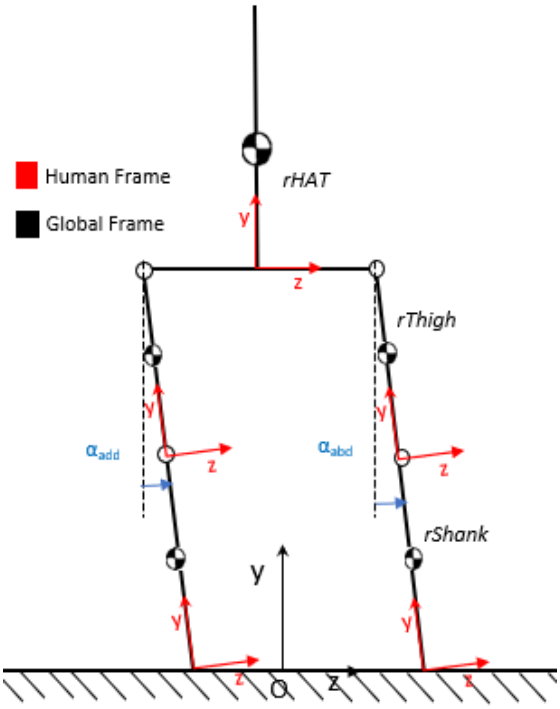

Figure 9. Model conventions in frontal plane

3.2.3 Center of mass calculation

Once computed the total CoM for the Exoskeleton and for the human, the total CoM_{EH} is calculated as:

$$CoM_{EH} = \frac{CoM_E\, M_E + CoM_H\, M_H}{M_E + M_H}$$

being M_E and M_H, CoM_E and CoM_H are the mass and the CoM of the Exoskeleton and human segment, respectively.

3.3 Data preparation for PIs calculation

Once the software interface has been closed, it will automatically store a set of raw data files called: `resampled_pusher.csv` and `resampled_smartgarment.csv`.

Subsequently, these data will be processed by a pre-processing algorithm, segmenting data in different pushes and converting renaming files in order to be compliant with the EUROBENCH software requirements.

Pre-processed data will follow the pattern below:

`subject_X_cond_Y_run_Z_[type].csv`

Such format provides the following information:

1. [type] is a string related to the type of information stored in the file.
2. X, Y, Z are integers respectively associated with the number of subjects involved, the number of different conditions being tested (ranges from 1 to 4 in case of Reduced Protocol and from 1 to 16 in case of Full Protocol selection), and the number of repetitions of the same perturbation (in our case from 1 to 5).

Finally, the user will obtain the following set of preprocessed data, ready to be processed by the PI algorithm:

1. `subject_X_cond_Y_run_Z_jointAngles.csv`*:* it contains the time-series of all measured joint angles, expressed in YXZ Cardan Angles, in the EUROBENCH data format (as recommended on the Plug-in Gait model from Vicon. The **minimum set of data to be measured** has to include left/right hip adduction/abduction, hip flexion/extension, knee flexion/extension and ankle dorsiflexion/plantarflexion. It is important the file contains these data in the proper data format, regardless the source of recording (IMUs, optoelectronic motion capture system, exoskeleton sensors, etc.).
2. `subject_X_cond_Y_run_Z_pushstick.csv`*:* a eight-columns csv file containing time-series of three force components and quaternion orientations measured by the perturbator, with the following labels:

time [sec]	**force_z** [N]	**force_y** [N]	**force_x** [N]	**q0**	**q1**	**q2**	**q3**

3. `subject_X_cond_Y_run_Z_smartgarment.csv`, it contains the four most active sensors and quaternion orientations measured by the smart garment, with the following labels:

time [sec]	**pressed_sensor1**	**pressed_sensor2**	**pressed_sensor3**	**pressed_sensor4**	**q0**	**q1**	**q2**	**q3**

4. `condition_Y.yaml`: it contains all information specified in the controlled variables, described in 2.3, as follows:
    - `perturbation_type`
    - `perturbation_magnitude`
    - `perturbation_duration`
    - `perturbation_orientation_pitch`
    - `perturbation_orientation_yaw`
    - `perturbation_location`
    - `exoskeleton`

5. `wr_segments.urdf`: it describes the physical and dynamical properties of each of the segments of the worn robot.
6. `subject_info.yaml`: it contains all the anthropometric measurements of the human body segments included in the model, in terms of lengths and masses (see also documentation at EUROBENCH data format), as follows:
    - `l_shank_length`
    - `l_shank_mass`
    - `l_thigh_length`
    - `l_thigh_mass`
    - `r_shank_length`
    - `r_shank_mass`
    - `r_thigh_length`
    - `r_thigh_mass`
    - `back_full_length`[2]
    - `back_full_mass`
    - `pelvis_w`

[2] The segment 'back full' named in the Human Model of the EUROBENCH data format corresponds to the HAT segment of our model.

This file can be prepared manually or by using the `BenchBalance_anthropometry.exe` application, whose interface is reported in Figure 9.

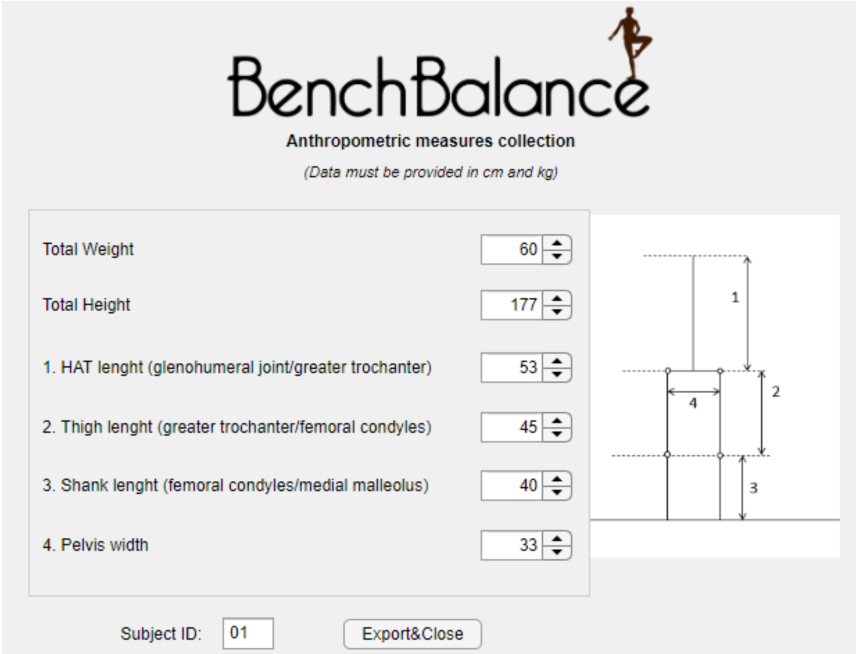

Figure 9. Interface of the application to export `subject_info.yaml` file.

All files must be compliant with the [EUROBENCH data format](#).

3.4 Overview of input and output files

The overview of input and output files for the benchmarking algorithm is reported in Figure 10.

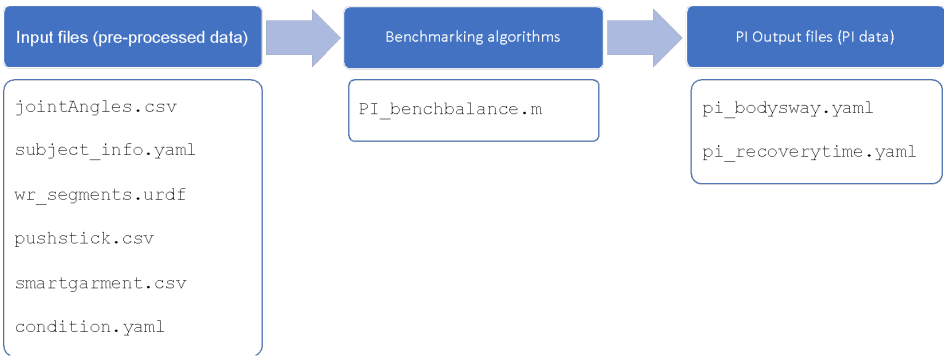

Figure 10. Scheme of input and output data for the BenchBalance algorithm.

The `jointAngles.csv` file can be generated regardless of the source of recording (IMUs, optoelectronic motion capture system, exoskeleton sensors, etc.) with the only constraint of having its format compliant with the [EUROBENCH data format](#).

4 Dataset

Testing dataset with a healthy user is included in subfolder [DATASET].

5 References

[1] Winter, David A. Biomechanics and motor control of human gait: normal, elderly and pathological. 1991.