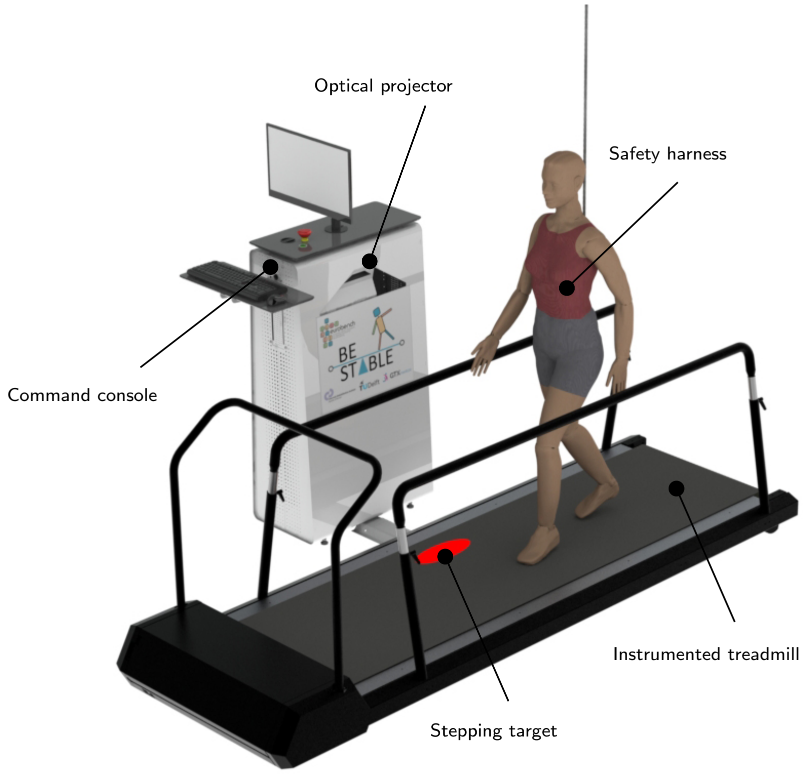


BESTABLE MANUAL V5

Table of Contents

1. Motivation and Design Criteria

To quantify balance of bipedal gait, for example to benchmark exoskeletons, prostheses or bipedal robots, a promising approach is to induce perturbations and to register the resulting subject responses. Examples of these perturbation devices are the wearable GyBAR, which can induce torques to the upper body, and the BAR-TM, a treadmill-based device that can apply lateral forces to the hip.

These mechanical gait perturbation devices, however, still have a low TRL score and due to the small (or non-existent) production volumes and expensive components, they are difficult to source and often require a high cost to produce. These disadvantages impede the widespread use of gait perturbations in clinical settings or to benchmark assistive devices or bipedal robots – only institutions with abundant financial resources and skilled personnel are able to acquire or produce these types of devices.

The aim of the BeStable platform is to be a low-cost alternative to mechanical gait perturbation devices, built up entirely by off-the-shelve, readily available components. Instead of relying on expensive mechanical actuators to apply mechanical perturbations, the gait perturbations are induced by persuading a person walking a treadmill to perturb themselves by changing their stepping pattern. The BeStable platform continuously tracks the walking pattern of a user and projects stepping locations on the treadmill surface that challenge the balance response of the user.

2. Technical Characteristics

2.1. Components of the BeStable system

BeStable testbed is composed of the following hardware and software components:

- Instrumented treadmill (Motek C-Mill) with six integrated force transducers
- Command console (part of Motek C-Mill) with D-Flow software
    - PC
    - Optical projector
    - National Instruments Data Acquisititon Board (NI USB-6210)
- Delsys IMU sensors with Delsys Trigno software
- Safety system
    - Safety Harness (3 different sizes)
    - safety rope with locking mechanism
    - 2 Ceiling Hooks (no wall screws included)

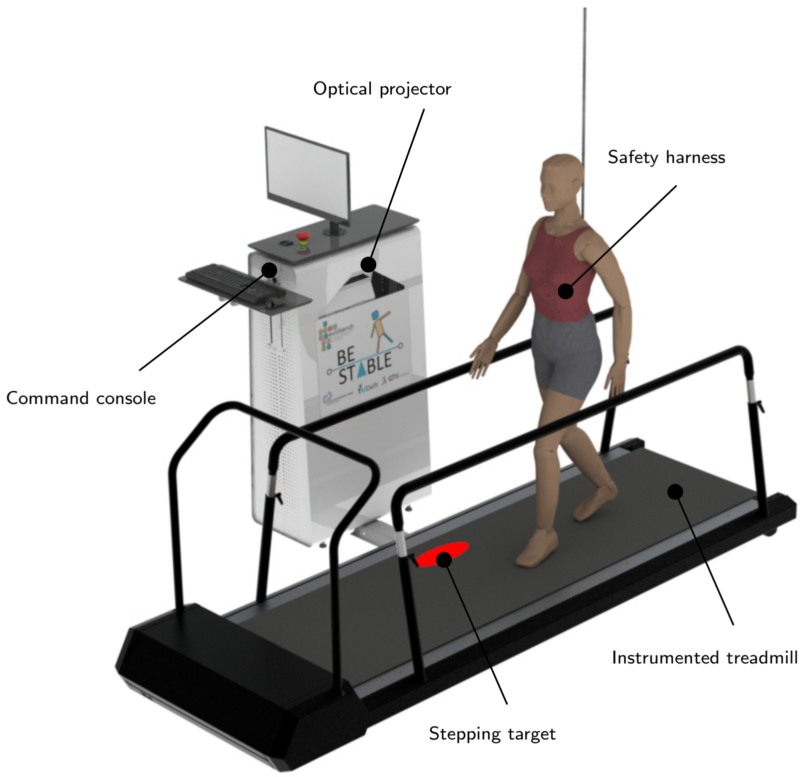


Figure 1: Render of the BeStable platform

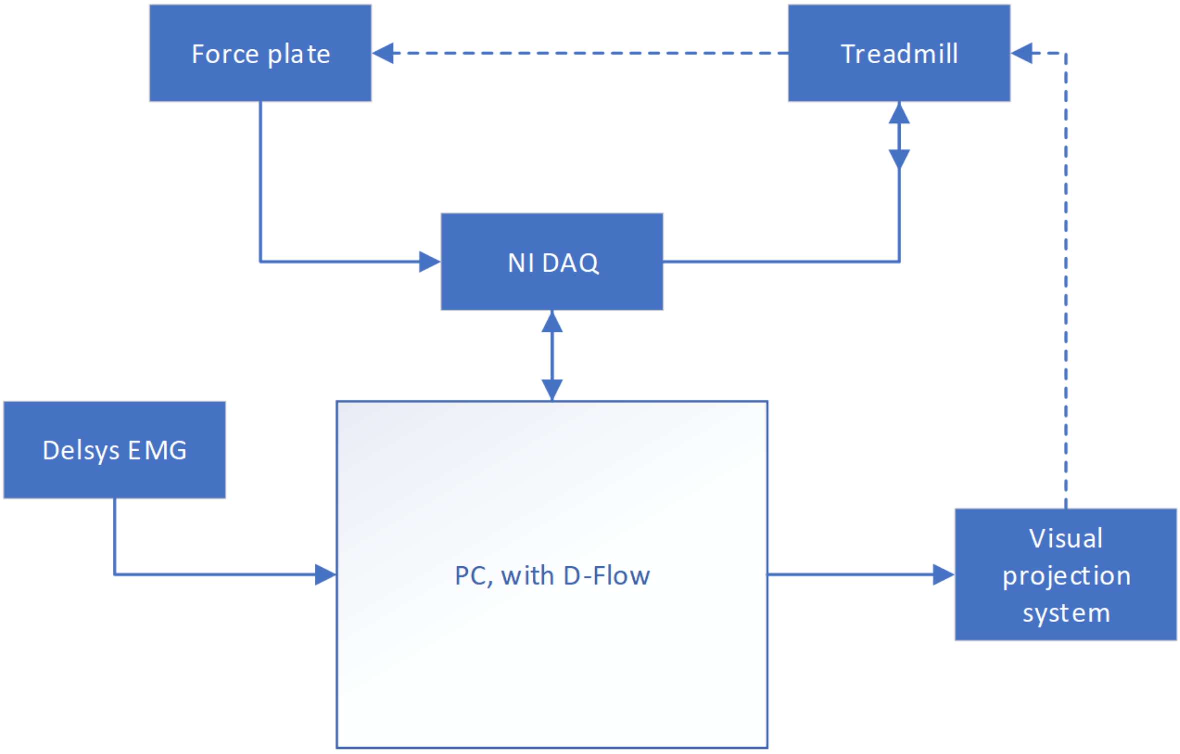


Figure 2: Components of the BeStable system

3. Testbed Use (Quickstart)

1) Turn on the green power switch at the front of the treadmill.

2) Turn on the power switch at the bottom of the PC cabinet. The PC and projector will turn on.

3) Login to the PC with the admin profile (user: **admin**, password: **admin**). (You can also login as operator, but is not recommended for D-flow as it needs admin rights)
4) **Optionally:** Pair the Delsys IMUs. Use the Delsys Trigno control utility computer program if needed for the pairing process. Also, you may want to ensure that for each IMU, the necessary sensors (Accelerometer, Gyroscope etc.) are turned on and are set to appropriate cut off limits (otherwise, the data may get clipped). This can be verified by clicking on each individual IMU icon in the Delsys Trigno control utility GUI. If not sure about the procedure, refer to Section 8.2 of this user manual.
5) **One time only:** Check the following files that need to be placed in the correct path:

File name	*Path*	*Notes*
Bestable_v10.caren Bestable_v10.dflow Bestable_v10.sceneconfig	D:\CAREN Resources\Projects\BeStable platform ver2\Applications	
protocol.yaml	D:\CAREN Resources\Projects\BeStable platform ver2\Protocols	This file is needed in the case of loading protocol parameters from file

bestable.lua gaitDetectionGTXLib.dll general.lua gtxLib.lua objectPlacement.lua protocol.lua uriLib.lua	D:\CAREN Resources\Projects\BeStable platform ver2\Scripts	Please refer to Section 8.1 for further details
left.wav perturbationsEnabled.wav protocolFinished.wav right.wav targetHit.wav targetMissed.wav	D:\CAREN Resources\Projects\BeStable platform ver2\Sounds	Files are needed in the case of enabling sounds

6) Start **D-Flow** software using the shortcut in desktop or from the start menu (Note: use D-Flow and not D-Flow Frontend!).
7) Open the latest version of our BeStable application (File�Open…�Browse to **D:\CAREN Resources\Projects\BeStable platform ver2\Applications\Bestable_v10.caren**)
   Note: a shortcut to "**Bestable_v10.caren**" is placed on the desktop.

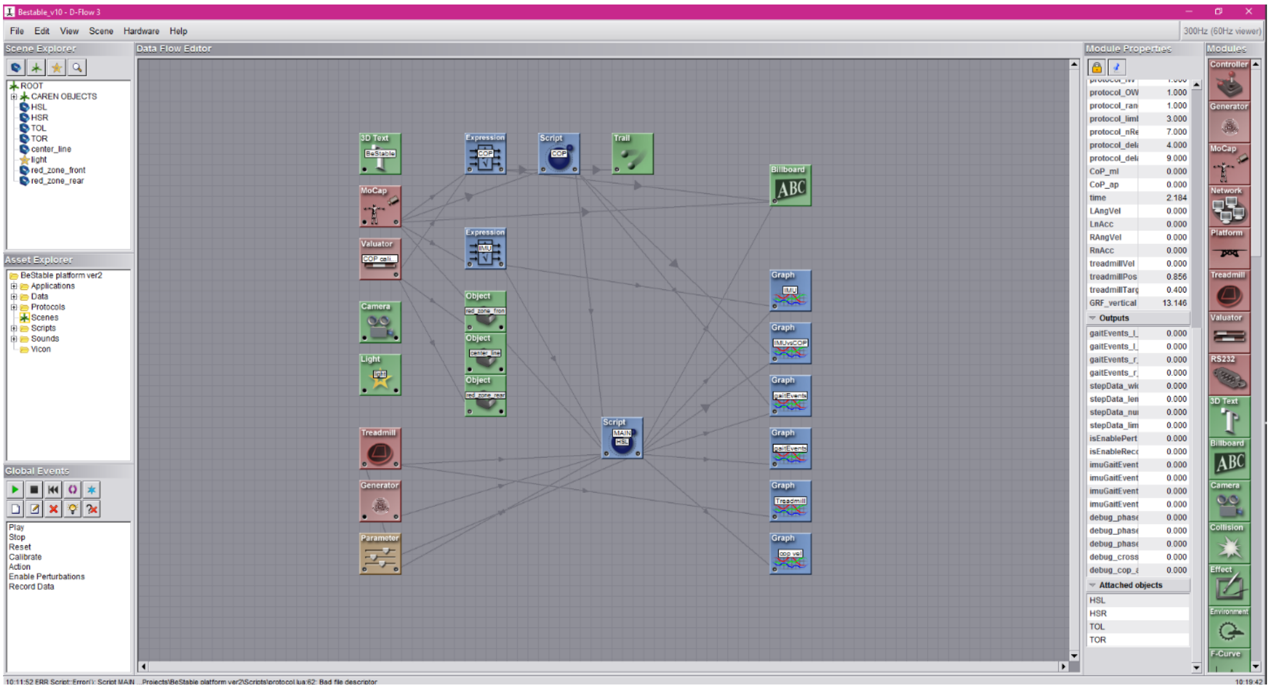


Figure 28: D-Flow Application

8) On the treadmill's control panel disengage the emergency stop (twist and it will pop up), press the black arrow button (Enter button). The message on the LCD screen should change from "Stop" to "Stand by". Press the "Enter button" again to enable the treadmill motor. The speed will be visible.

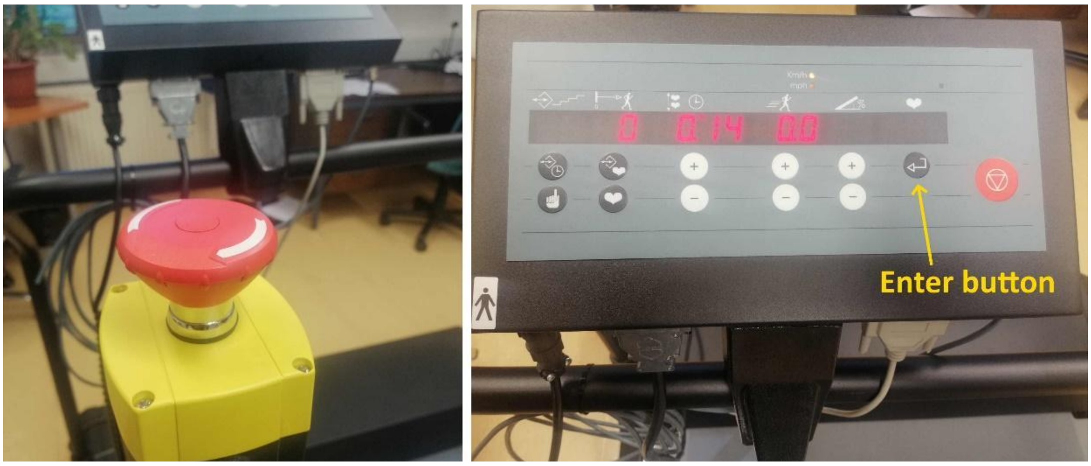


Figure 29: left - safety switch; right - enable treadmill motor

9) **Optionally:** Walking zone dimensions can be can be set with the **red_zone_front**, **red_zone_rear** in the valuator block "**COP calibration parameters**".

10) Double click on the MoCap module, ensure that it is in "**Live**" mode, calibrate the force plate by clicking on the calibrate button in analog tab. Refer to [Section 6.2](#) for further details.

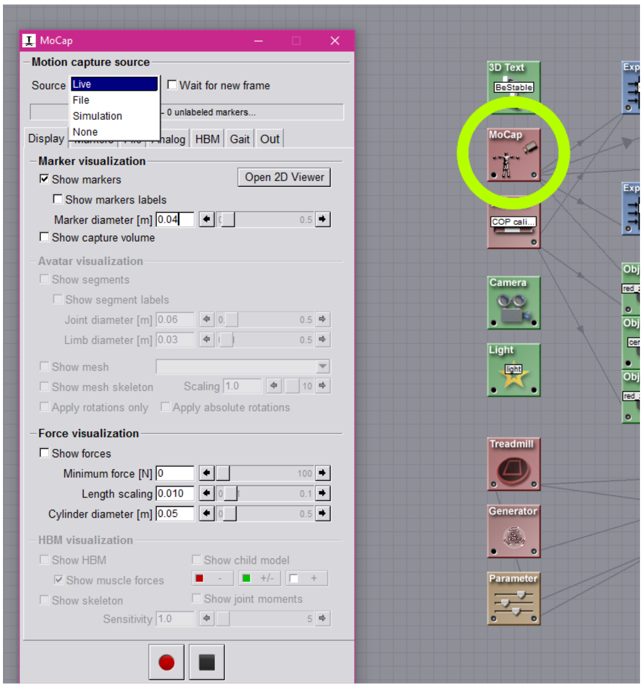
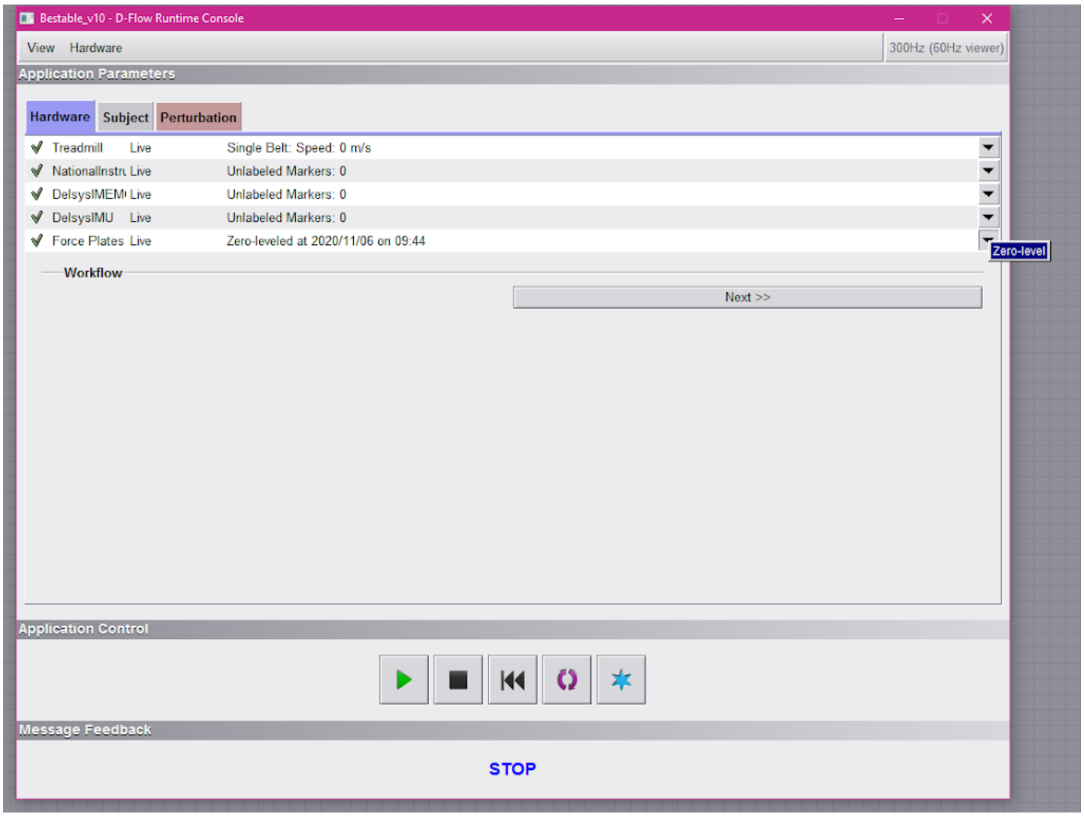


Figure 30: Mocap Module

11) Open View⍰Runtime Console (shortcut **F2**), where the parameters of the subject and protocol can be selected.



Note: In "**Hardware**" tab, force plates can also be zero-levelled here. All hardware from the list needs to be checked in order to proceed with the "**Next >>**" (at the first use it is labelled as "**Acknowledge**") button.

12) After clicking "**Next >>**" button from the "Hardware" tab, the subject characteristics should be set in the "**Subject**" tab.

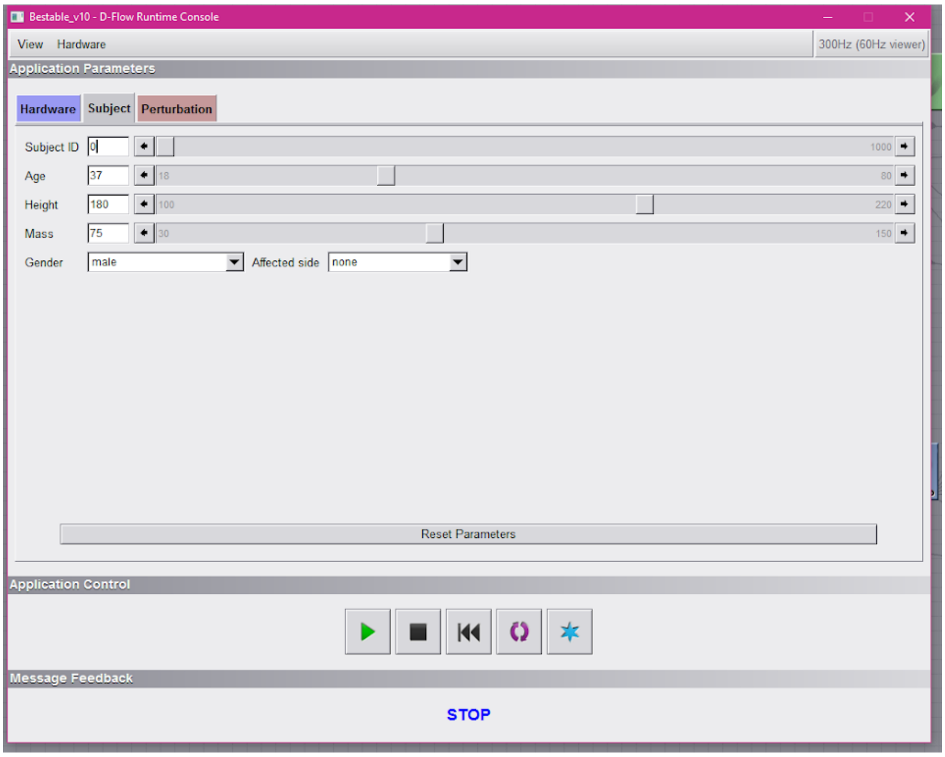


Figure 32: Runtime console –subject parameters

13) In the “Perturbation” tab, select custom protocol parameters (including treadmill speed) or check “**Import protocol from …**”, which loads protocol parameters from the “**protocol.yaml**” file located in “**D:\CAREN Resources\Projects\BeStable platform ver2\Protocols**”. For more details see Section ???.

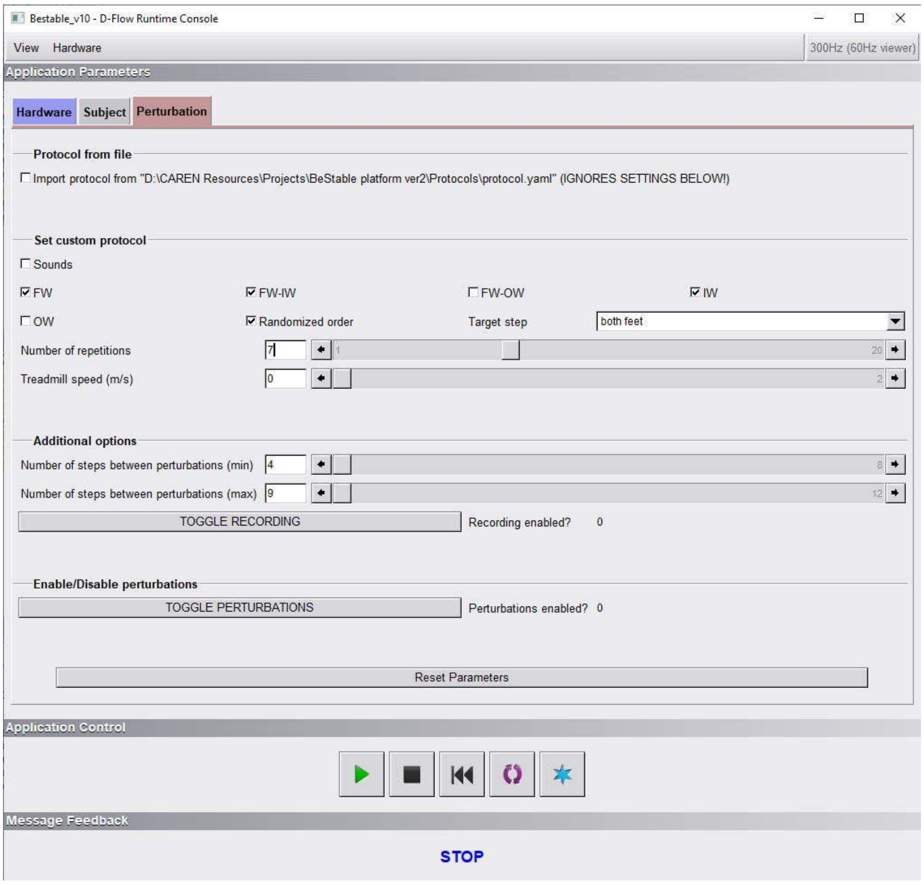


Figure 33: Runtime console - Perturbations

Note 1: The treadmill will not run until “Play” button is pressed.
Note 2: Data recording is enabled by default.

14) **Optional:** If measurement of foot acceleration and rotational velocity is required, place the IMU sensors on the foot (as described in section 3.3)
15) Put the safety harness on a subject and ask the subject to step on a treadmill positioned with the feet on the central line projected on the treadmill surface. Attach the safety harness on a safety hook.

Figure 34: Standing on the BeStable platform

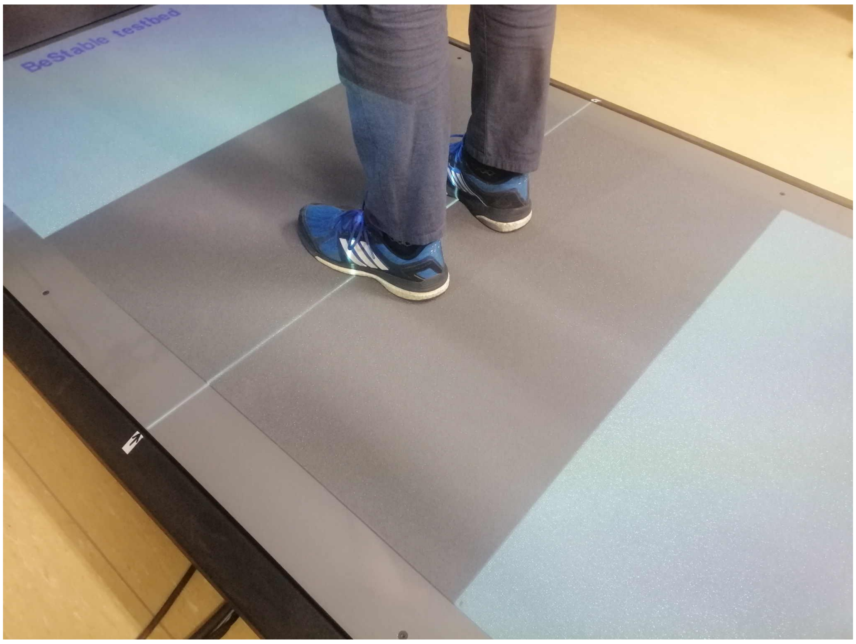


Figure 35: Foot position on BeStable platform

16) It is suggested to open the “**Main script**” window in order to monitor program states.

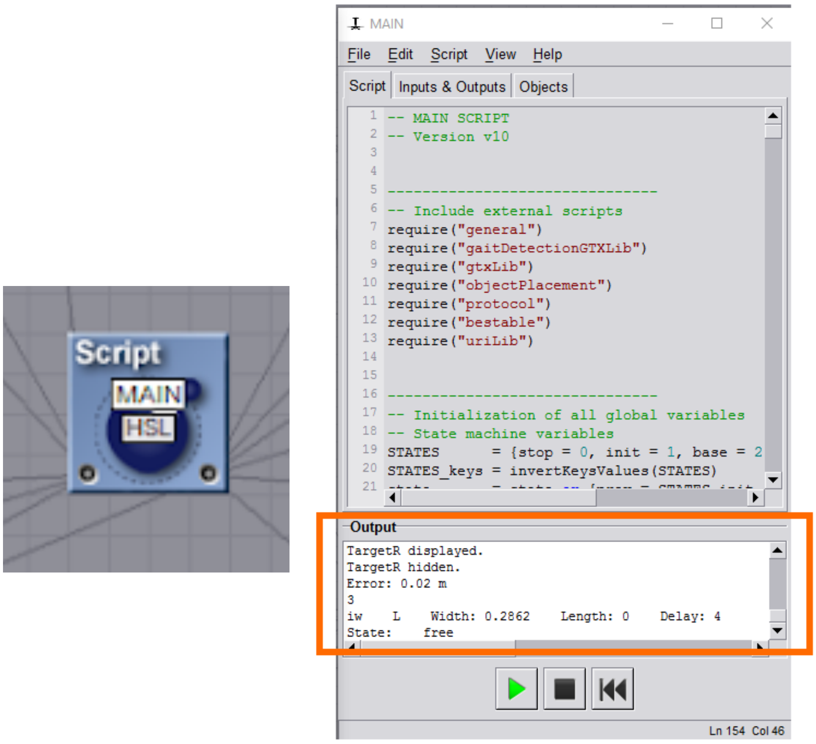


Figure 36: Main Script Block – Output monitor

17) To start the experiment, press the “**PLAY**” button in the runtime console.

<u>Note</u>: Sometimes the error “Script time out” might appear in the Output window of the main script for an unknown reason. In this case, press the “STOP” button in the “Runtime console”, press the “REWIND” and start again by pressing the “PLAY” button.

18) Press the “**TOGGLE PERTURBATIONS**” button in the runtime console when you want to apply perturbations as selected from the “**Perturbation**” tab. The new target steps will appear based on reference positions of the Left Toe-Off (LTO) or the Right Toe-Off (RTO) points. The perturbations will be automatically disabled after finishing the protocol. See more details in Section ???.
19) Press the “**STOP**” button when you want to stop. This will also stop the recording module and save files to the folder named “subject ID” (example: subject ID 15) in the following location:
<u>D:\CAREN Resources\Projects\BeStable platform ver2\Data\subject 15\</u>

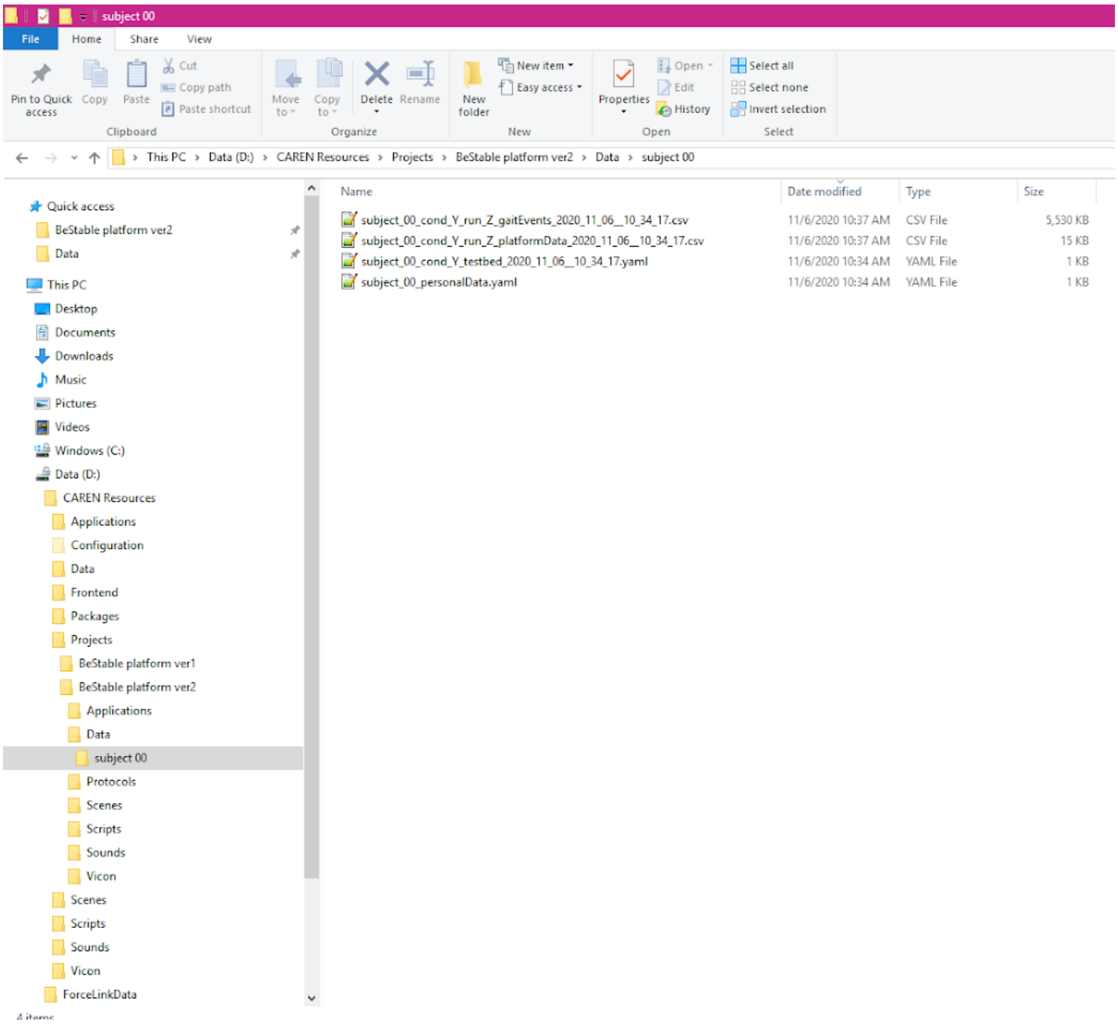


Figure 37: Data Location

Figure 1: BeStable testbed – instrumented treadmill and the cabinet with PC, projector and Delsys system.

4. Configuration

4.1. Trigno wireless inertial measurement units (IMUs)

Turning on and pairing the Trigno sensors is described in detail in the Trigno Avanti user manual (page 17)

- The sensor must first be charged. The arrow glowing orange indicates that the sensor is charging, the arrow glowing green indicates that the sensor is fully charged.
- If not in the charger already, place the sensor in the charger for at least 3 s to reset the power settings
- Remove a sensor
- … more steps

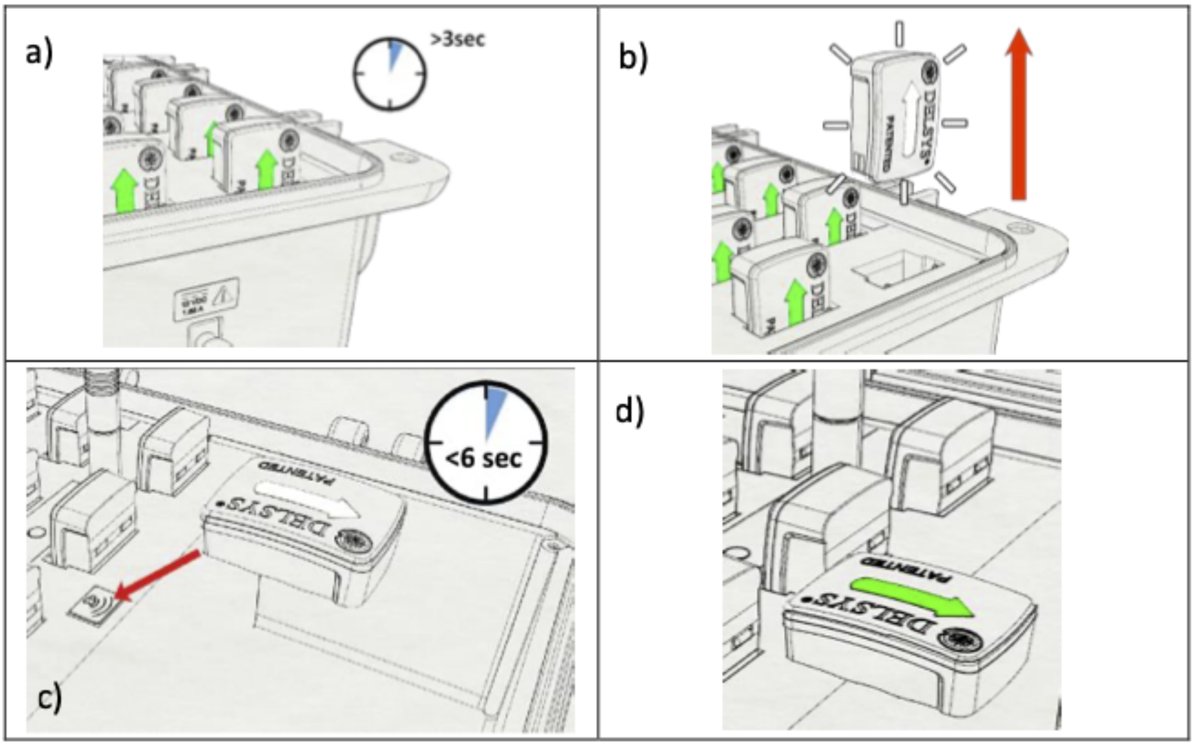


Figure 3: Pairing the Delsys IMUs

Meaning of the blinking patterns

- Base station (pp 14)

	State	Color	Pattern	LED Display
1	Power Off	Off	none	
2	Standby	Green	solid	
3	Data Streaming	Green	flashing	/
4	Communication Error	Green	double flash	/

Figure 4: Blinking pattern base station

- IMU sensor (pp 11)

	State	Color	Pattern	Arrow Display
	Common States			
1	Power Off	Off	none	
2	Power On/Activate	White/Green	fade	/
3	Charging	Amber	solid	
4	Charge Complete	Green	solid	
5	Identification Mode	White	rapid flash	/ /
6	Scan (Startup)	Amber/Cyan	slow flash	/
7	Power Up Error	Red	slow flash	/
	Trigno RF Mode			
8	Scan (Base)	Amber/Green	Slow flash	/
9	Low Power Scan (Base)	Amber	Occasional Flash	/
10	Data Collection (Base)	Green	slow flash	/
11	Configuration Change (Base)	Green	rapid flash (3x)	/ /
12	Pairing (Base)	Amber	solid	
13	Pairing Success (Base)	Green	rapid flash (≥6x)	/ /
14	Pairing Fail (Base)	Red	double flash(≥3x)	/ /
	BLE Mode			
15	Advertise (BLE)	Cyan	Slow flash	/
16	Low Power Advertise (BLE)	Cyan	occasional flash	/
17	Data Collection (BLE)	Blue	slow flash	
18	Idle (BLE)	Magenta	slow flash	

Table 1: Sensor LED functions

Figure 5: Blinking pattern IMU sensors

References:

- Trigno Avanti product page
- Trigno Avanti user manual

4.2. IMU configuration for Gait detection

The IMU data is used to perform gait event detection in real time.

Setting up the IMU gait detection library:

The library API is packaged in the dll file **"gaitDetectionGTXLib.dll".**
This file should be copied and placed in the following path: **D:\CAREN Resources\Scripts**, where D: is the drive where D-Flow configuration is installed.
If the dll file is not found in the location cited above, it can be copied from the path of the BeStable D-Flow application (**D:\CAREN Resources\Applications\Script12**).

Configuring the IMUs for gait detection in D-Flow:

The IMU gait detection algorithms use data from two IMUs, each one placed on one foot of the user. The current system uses two Delsys Trigno™ IMUs. Follow the steps below to power up, pair and configure the Delsys IMUs.

Figure 6: Delsys IMU case

Figure 7: Delsys IMU

1. Power up the IMU case by connecting it the power supply.
2. Connect the IMU case by USB to the main computer.
3. Take out the IMUs tagged with the numbers 1 and 2 out of the case.

Note: At this stage, if you notice that the IMUs are already paired and connected to the computer (The IMUs' arrows should light up in green and blink slowly), you can already jump to step 9 in order to check that the sensors are correctly configured in the Delsys Trigno™ control utility. If the sensors' arrows are lighting up in purple, it means that they were not paired correctly to the system. To pair them, follow the next steps.

4. From the desktop, open Delsys Trigno™ control utility.

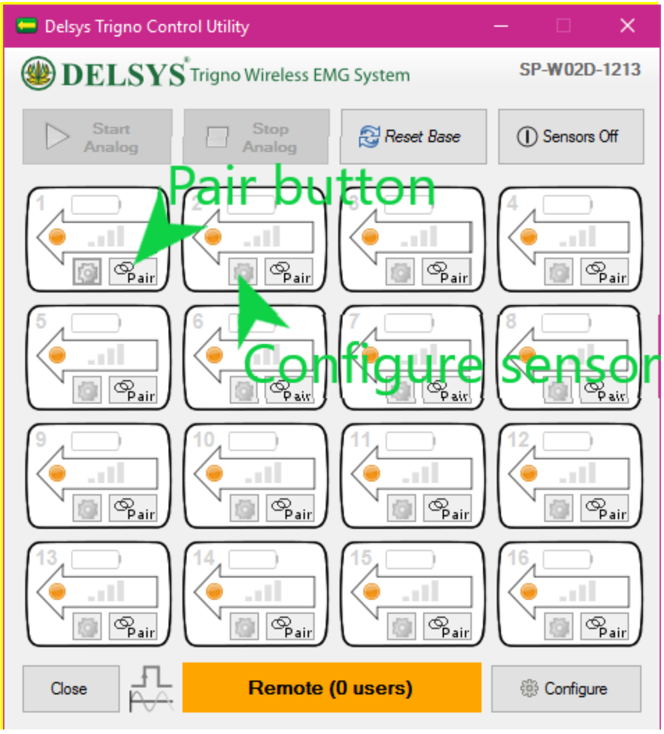
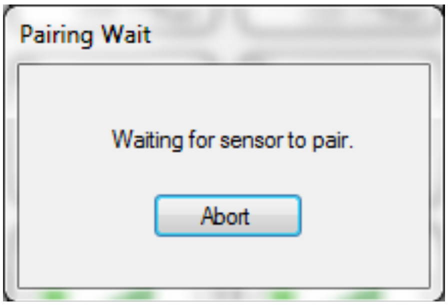
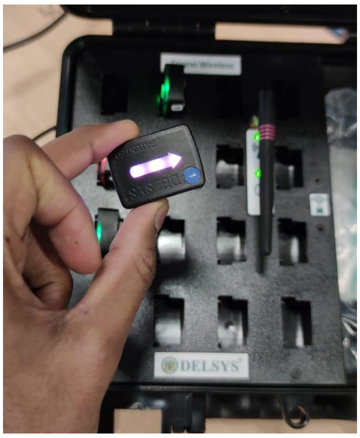


Figure 8: Trigno Control Utility main screen

5. To pair sensor number 1 (respectively sensor 2), click on the pair button in the area where number 1 (respectively number 2) is written. The following popup window will appear, showing that the software is waiting for a sensor to pair.





6. Take sensor 1 (respectively sensor 2) out of the Delsys case.

7. Put the IMU close to the region highlighted in green in the picture and hold it still for one or two seconds.

8. Wait until the light of IMU turns green. At the same time, a popup window will appear, confirming the pairing.

9. After successfully pairing each IMU, click on the button with a gear icon next to the pairing button of each sensor. Then make sure configure the sensors as follows:
    a. Put Inertial Data to 'All'.
    b. Set accelerometer range to ±16g.
    c. Set gyroscope range to ±2000dps.

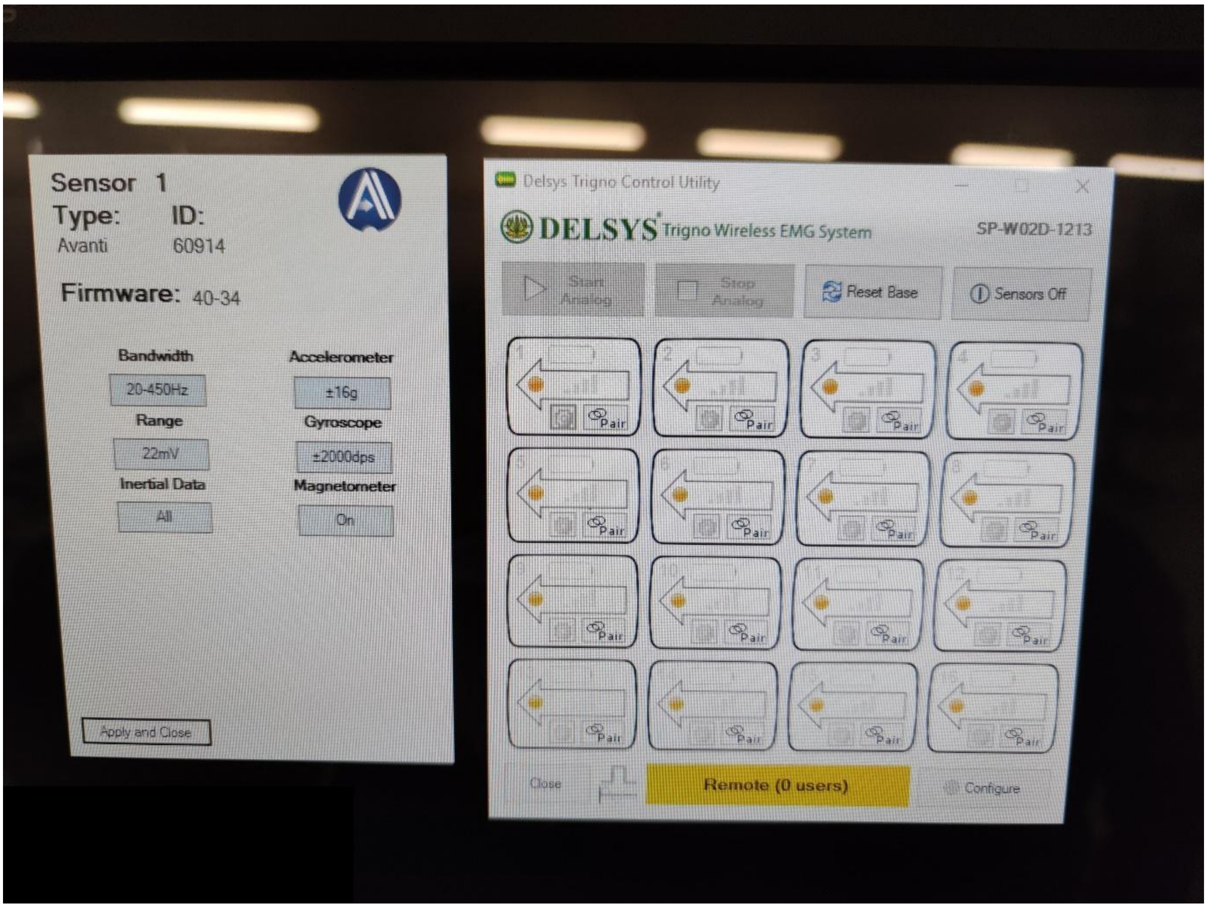
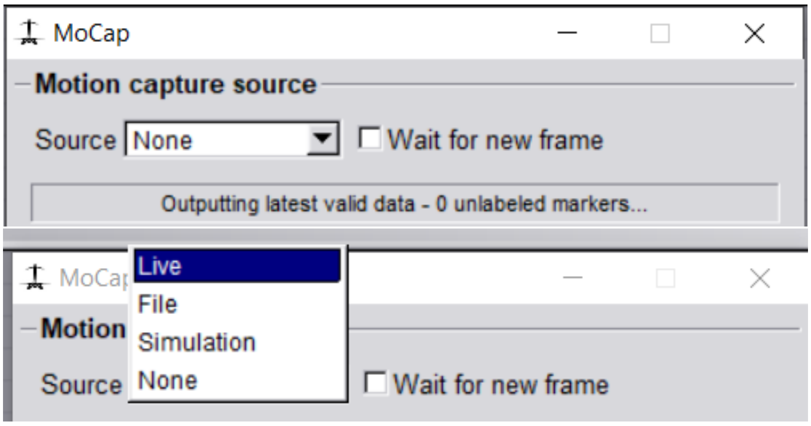


Figure 9: Sensor configuration

10. Open D-Flow, load the BeStable D-Flow application and double click on the graph module that has **IMU** written on its icon. Check that the IMU readings are successfully plotted in the graph.

If no data is plotted, close D-Flow, open the Delsys Trigno Utility, check the pairing and configuration of the sensors. If yes, click on the button “Reset Base”, check that the sensors are still connected. Then, reload the BeStable application in D-Flow, double click on the MoCap module and check that the source is set to “Live”.



4.3. IMU foot placement:

Once the IMUs are successfully paired and the MoCap is successfully streaming IMU data in D-Flow, the IMUs can be placed as follows:

- The IMU tagged with the number 1 must be placed on the left foot.
- The IMU tagged with the number 2 must be placed on the right foot.
- The arrow of each IMU must be pointing upwards with respect to the ground.

Figure 10: IMU placement on left foot

Figure 11: IMU placement on right foot

-

4.4. N-mill integrated force plate

Connecting the force plate to the NI data acquisition board, which is located in the cabinet station. The sensor cables are labelled in pairs (red = +, white = -) and must be inserted in the following ports:

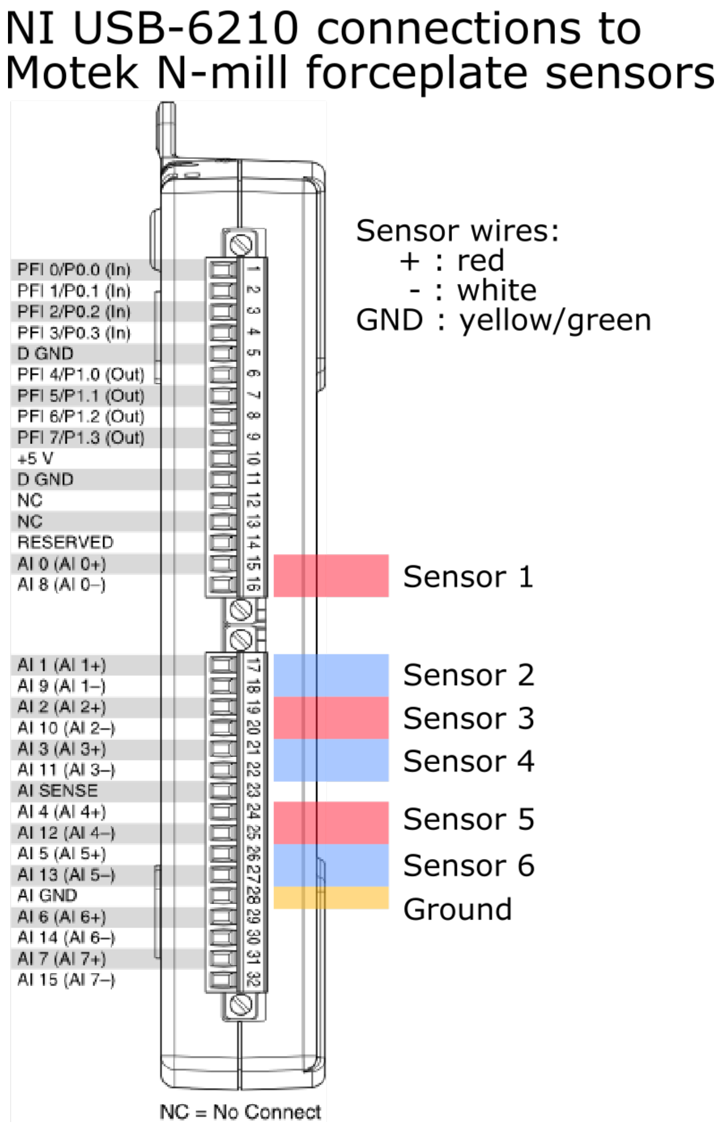


Figure 12: Connection of force sensors to DAQ

References

- NI USB-6210 product page
- NI USB-6210 pinout description

4.5. Treadmill and visualization:

Visual projector is projecting to the walking surface of the instrumented treadmill the following visual objects:

- white line showing central position of the treadmill (see Fig. below - center line)
- front and rear light red areas (red_zone_front and red_zone_reare) visualizing the border of walking (can be adjusted as needed)
- instantaneous center of pressure (COP, yellow circle) location with its tail of the laste gait cycle length
- the positions of the COP, where left toe off (LTO, red point) and left heel strike (LHS, red point) were detected
- the positions of the COP, where right toe off (RTO, light green point) and right heel strike (RHS, light green point) were detected
- the average positions of RTO (red circle) and LTO (blue circle) of the last 3 gait cycles

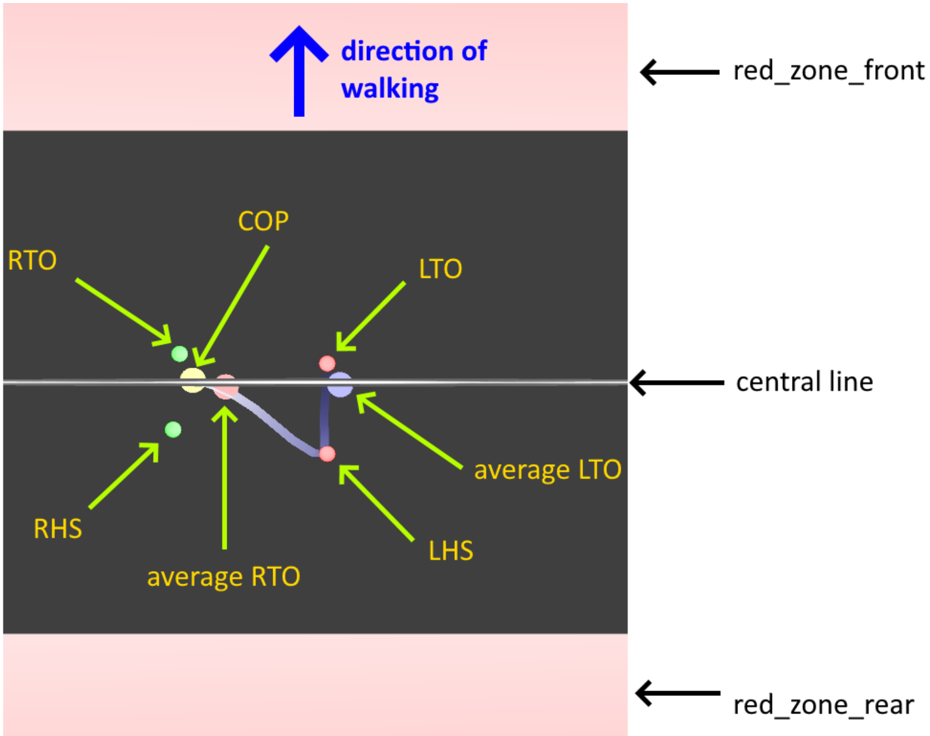


Figure 13: Testbed visualization on the treadmill walking surface

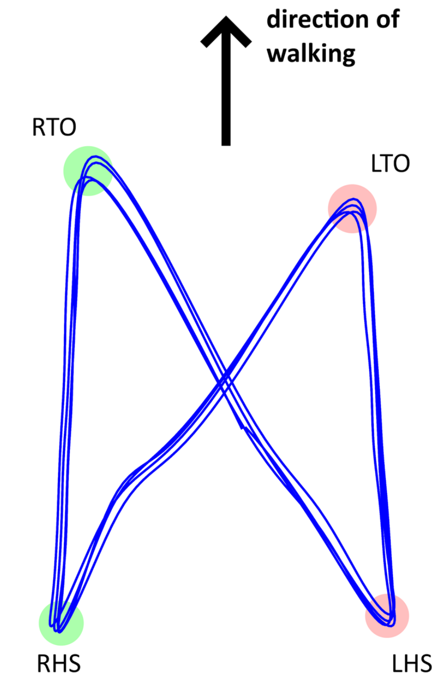


Figure 14: Gait events on the COP walking pattern

Visual cues are appearing in the perturbation mode, when the “perturbation toggle button” is pressed (D-Flow Runtime Console, Perturbation tab). If a blue visual cue (blue ellipse) is shown, the subject needs to step on it with the right foot. If a red visual cue (red ellipse) is shown, the subject needs to step on it with the left foot. When particular visual cue is projected on the treadmill, it is stationary positioned and does not move with the treadmill speed.

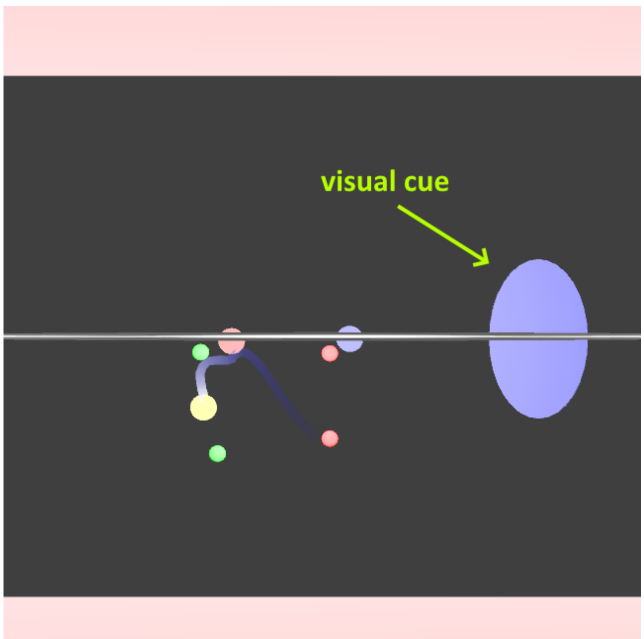
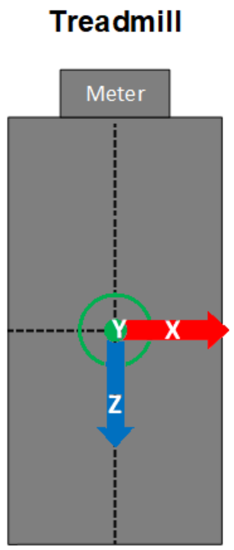


Figure 15: Example of the visual cue appearance for the right foot desired location

4.6. Coordinate systems

Force plate coordinate system



The force plate coordinate system is placed in the center of the treadmill:

- X coordinate in the mediolateral direction (positive to the right),
- Y coordinate in the transverse direction (positive up),
- Z coordinate in the anteroposterior direction (positive to the backward).

Subject is walking in the direction of a negative z coordinate.

Visual projection coordinate system

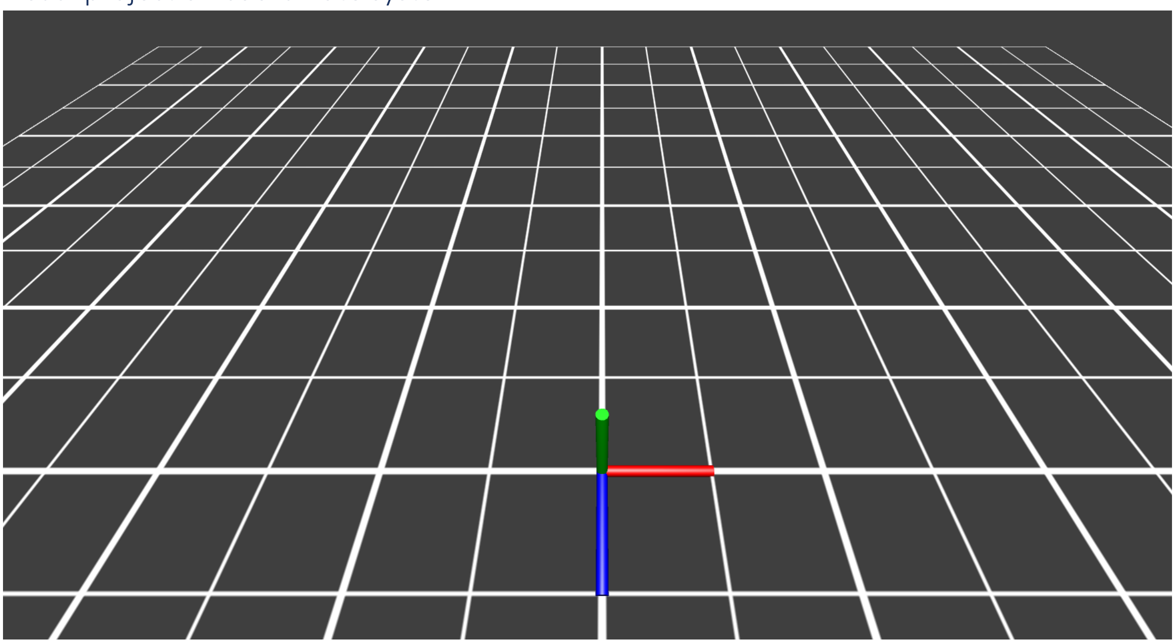
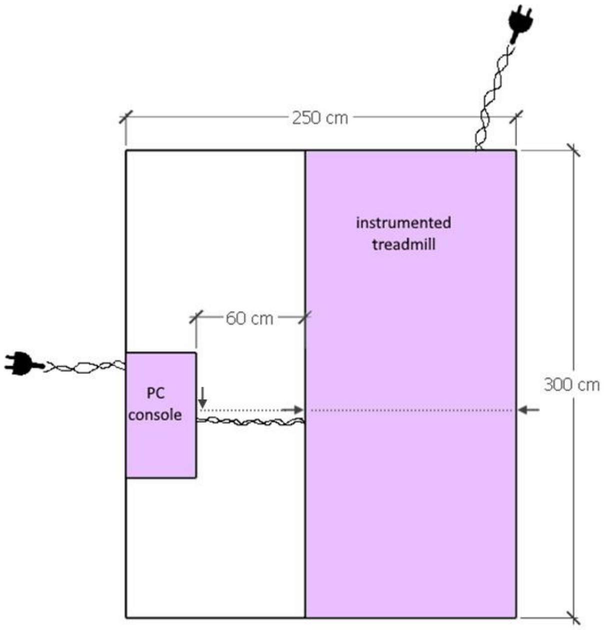


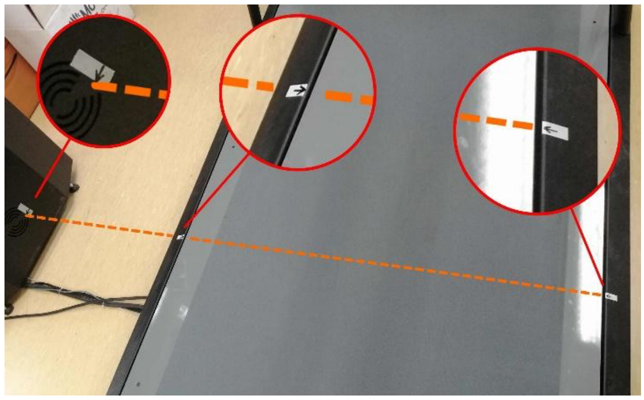
Figure 17: Visual projection coordinate system (RGB in the image corresponds to XYZ respectively)

Overlapping the coordinate systems

The two coordinate systems described above are by default not overlapping. It's therefore necessary to overlap them explicitly. If the PC console and the treadmill are positioned as in the figure below, there should not be major deviations in overlapping the coordinate systems.

If you do have any problems, it is advised to call in the support of Motek. If you want to fix it yourself, you can try the following steps. First, make sure that the projector, which is mounted on the PC console, is calibrated to make projections only on the walking surface of the treadmill. This should be done according to the Motek support team instructions.



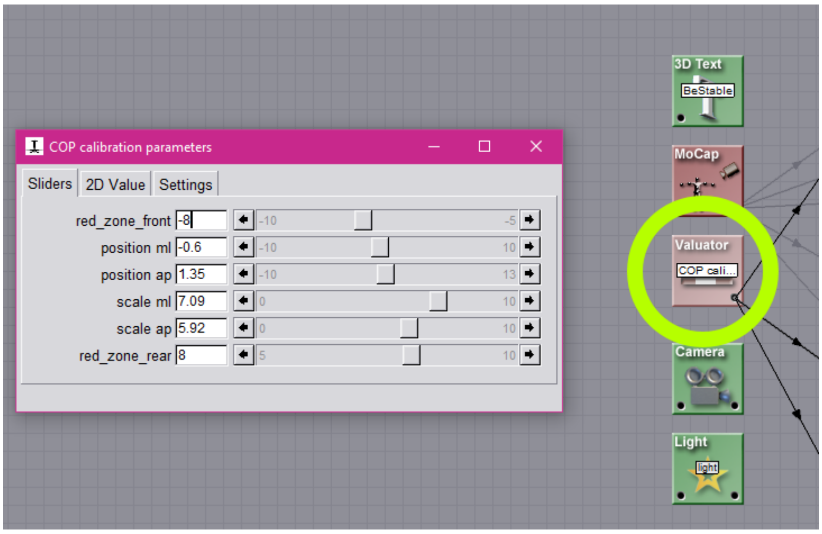


if the positions of the treadmill as in Figure 6 and the cabinet station are ensured. Distance between cabinet station and treadmill is 60 cm. Three arrows (two on treadmill and one on PC console) indicate positions, which should be in line.

Here are the instructions to adjust the coordinate systems:

1) Power up the PC console and treadmill, login to Windows as admin (username: admin, password: admin)
2) Open D-Flow software and run the latest version of the BeStable application (File⍰Open…⍰Browse to **D:\CAREN Resources\Projects\BeStable platform ver2\Applications\Bestable_v10.caren**). A shortcut to "**Bestable_v10.caren**" is also placed on the desktop.
3) Open Runtime Console (shortcut F2), zero-level the force plates (refer to Force Plate Calibration section) and press the "Acknowledge" button. Go to "Perturbation" tab and set Treadmill speed to 0 m/s!!! Then press the "PLAY" button.
4) In the DRS window of the D-Flow software, show the coordinate system (type "a") and grid (type "g").
5) Mark up the center of the treadmill by using tape and pen. Note that the central line is marked with two arrows on each side of the treadmill. Measure and mark up the central point between these two arrows.
6) Open Camera block (refer to Camera block section), and adjust X, Y and Z translation parameters in order to move the origin of the coordinate system to the center of the treadmill.

7) Open the Valuator block “COP calibration parameters” (refer to COP related blocks section) and adjust COP object (yellow circle) with the x and z offsets (**position_ml**, **position_ap**, **scale_ml**, **scale_ap**) by using a stick.
8) Press with a stick at random location on the treadmill surface and adjust the x and z offsets (**position_ml**, **position_ap**, **scale_ml**, **scale_ap**) until the CoP appears in the correct location.
9) Press with a stick at one of the corners of the treadmill and adjust the x and z scales until the CoP appears in the correct location. Repeat at other locations until a suitable compromise has been achieved for visualization accuracy across the treadmill surface. Note that the mapping is not perfectly linear due to different sensor sensitivities, camera perspective, etc.



5. Protocols

5.1. Input

Several protocols may be built from the D-Flow Runtime console, where the perturbation parameters can be either imported from file "**protocol.yaml**" (located in "D:\CAREN Resources\Projects\BeStable platform ver2\Protocols") or they can be manually set (D-Flow Runtime console/Set custom protocol). The protocol parameters are listed below.

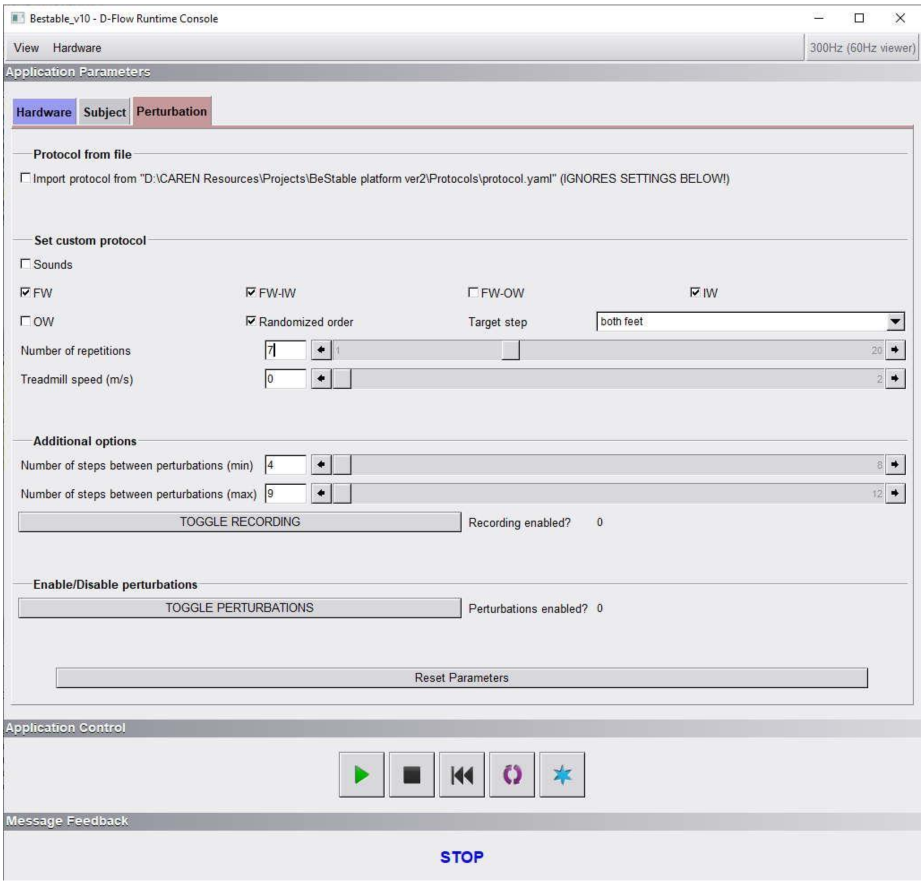


Figure 20: Protocol settings in the Perturbation tab of the D-Flow Runtime console

- Selection of different visual cue directions: FW, FW-IW, FW-OW, IW and OW (see figure 8);
- Selection of target step with options of only left foot, only right foot or both feet;
- Randomization of visual cues being triggered;
- Number of repetitions of particular visual cue direction per each foot;
- Enabling/disabling sound as an additional information for target step appearance. When a left or right visual cue appears, the system sound is triggered saying "left" or "right", respectively. When pressing the "toggle perturbations" button, the system triggers sound "perturbations enabled". After finishing protocol, the system triggers sound "protocol finished".
- Treadmill speed in meters per second
- **Optionally**, the number of steps between two consecutive perturbations (min, max) can be adjusted in order to increase or decrease recovery time after perturbation is triggered, before another perturbation is applied.

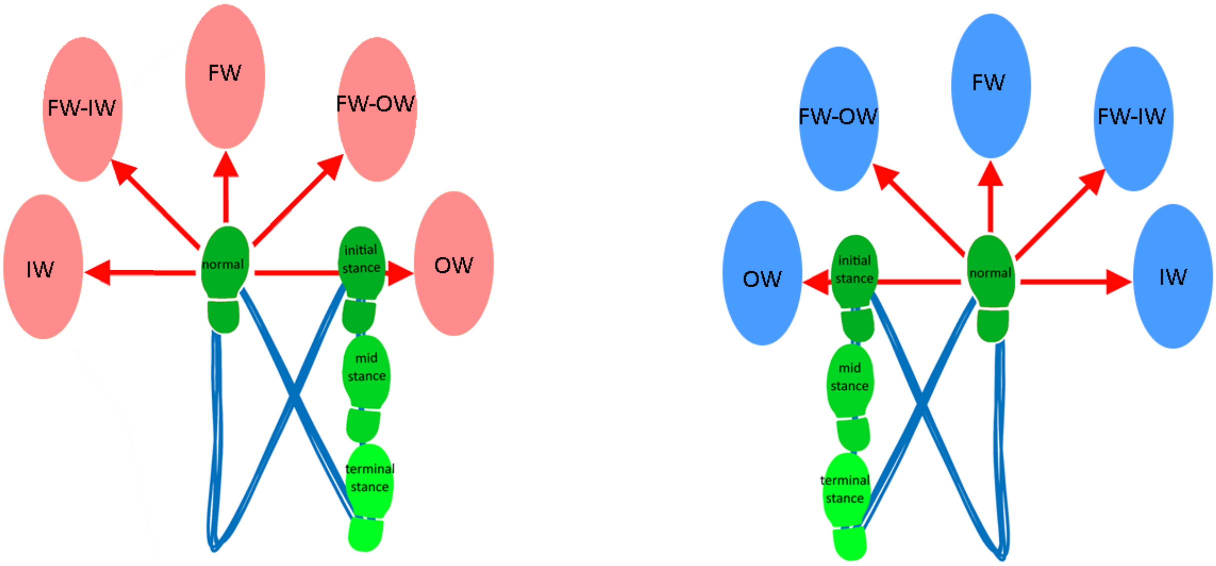


Figure 21: Visual cues for the left foot (left picture) and visual cues for the right foot (right picture)

<u>Note:</u> The distance between normal COP placement (see “normal” footstep in Fig. 8) and the visual cue - also denoted as the perturbation amplitude - is based on a subject leg length, which is approximated by the human height:limb ratio (Winter2009, "Biomechanics and motor control of human movement", pp 83). The amplitude is calculated as

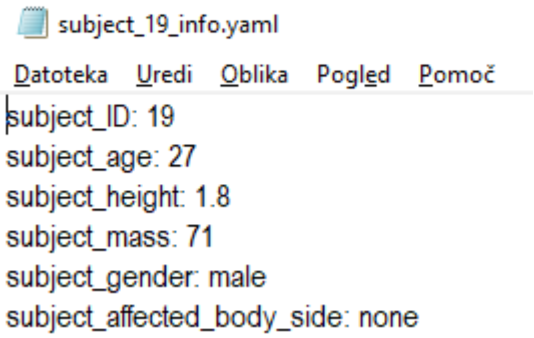
$$\text{leg\_length} = 0.530 * \text{subject\_height}$$
$$\text{perturbation\_amplitude} = \text{leg\_length} * 0.3$$

Parameter 0.3 was arbitrarily selected based on the experimental testings in order the perturbation amplitude is not too large or too low.

5.2. Recording data

After hitting the PLAY button in the D-Flow Runtime console the treadmill starts to run at the desired speed and the system starts recording by default. The following files are created:

- "**subject_X_info.yaml**" (subject characteristics)



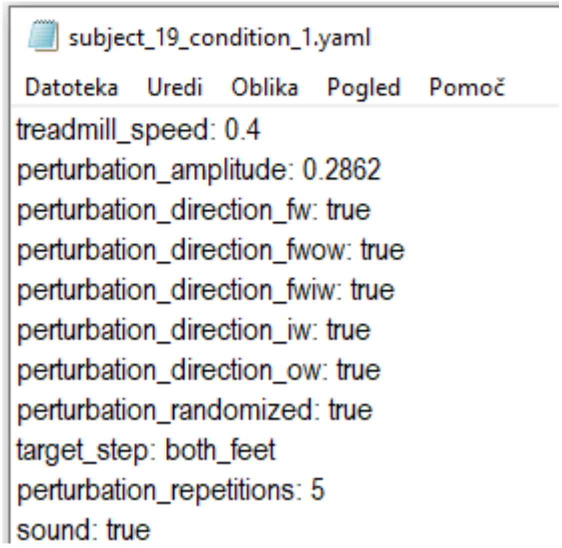
subject_19_info.yaml

Datoteka Uredi Oblika Pogled Pomoč


```
subject_ID: 19
subject_age: 27
subject_height: 1.8
subject_mass: 71
subject_gender: male
subject_affected_body_side: none
```


Figure 22: Example of "subject_X_info.yaml"

- "**subject_X_condition_Y.yaml**" (protocol settings used in the current run)



subject_19_condition_1.yaml

Datoteka Uredi Oblika Pogled Pomoč


```
treadmill_speed: 0.4
perturbation_amplitude: 0.2862
perturbation_direction_fw: true
perturbation_direction_fwow: true
perturbation_direction_fwiw: true
perturbation_direction_iw: true
perturbation_direction_ow: true
perturbation_randomized: true
target_step: both_feet
perturbation_repetitions: 5
sound: true
```


Figure 23: Example of "subject_X_condition_Y.yaml"

- "**subject_X_cond_Y_run_Z_platformData.csv**" (step-stamped data with performance indicators - PI),

	A	B	C	D	E	F	G	H	I
1	step_number	time_stamp	limb_initial	limb_final	step_width	step_length	step_time	target_error	message
2	1	0.692540373	R	L	0.00641961	-0.161693152	0.28	-1	free
3	2	0.87920704	L	R	0.011374518	0.034722497	0.376666667	-1	free
4	3	1.162540373	R	L	-0.000900878	0.08980198	0.376666667	-1	free
5	4	1.9724352	L	L	0.106615024	0.039941531	0.137014542	-1	free
6	5	2.932551324	L	R	0.18479253	0.642260597	1.229546951	-1	free
7	6	3.999615787	R	L	0.190906451	0.505797399	1.01051392	-1	free
8	7	5.106282453	L	R	0.181648059	0.448372055	1.106666667	-1	free
9	8	6.2000288	R	L	0.194259886	0.344007066	1.146666667	-1	free
10	9	7.30487168	L	R	0.211606079	0.539766365	1.15192256	-1	free
11	10	8.453878969	R	L	0.214195151	0.382900409	0.954621724	-1	free
	...	...	...	...	...	...	...	...	...
198	197	209.2684766	L	R	0.134782919	0.435448956	1.136623076	-1	free
199	198	210.3051433	R	L	0.122161689	0.382936332	0.97	-1	free
200	199	211.0884766	L	R	0.128802529	0.413897959	1.04	-1	Pert: ow (L)
201	200	211.2518099	R	L	-0.003557686	0.086207305	0.34	-1	action
202	201	211.6418099	L	R	0.003702075	0.084415543	0.2	0.118006283	target missed
203	202	212.1018099	R	L	0.051558147	0.158431423	0.46	-1	free
204	203	212.7487147	L	R	-0.197415456	0.260370445	0.500238151	-1	free
205	204	213.2874302	R	L	0.095712169	0.09027176	0.552048782	-1	free
206	205	214.1684715	L	R	0.327838424	0.40335707	0.956666667	-1	free
207	206	215.1122279	R	L	0.153394122	0.303828864	0.811464391	-1	free
208	207	216.0309312	L	R	0.161632229	0.348308399	0.851410204	-1	free
209	208	216.8946629	R	L	0.154858166	0.364485691	0.931024782	-1	free
210	209	217.8393572	L	R	0.141244129	0.380485243	0.931360924	-1	free
211	210	218.5960238	R	L	0.174391894	0.424002472	1.04	-1	free
212	211	219.7216914	L	R	0.206423636	0.479695717	0.78	-1	free
213	212	220.7158758	R	L	0.173953549	0.367610795	0.906518613	-1	Pert: ow (R)
214	213	221.3492091	L	R	-0.063639206	0.354133184	1.013333333	-1	action
215	214	222.2114987	R	L	-0.114803777	0.252333801	0.500470613	0.054068679	target hit
216	215	223.3201734	L	R	0.093751943	0.455221816	1.200493653	-1	free
217	216	224.333072	R	L	0.117691368	0.283039944	0.972898631	-1	free
218	217	225.3864053	L	R	0.125389113	0.548632388	1.253333333	-1	free
219	218	226.5739703	R	L	0.126939312	0.408795257	0.973333333	-1	free
220	219	227.680637	L	R	0.134075339	0.492272365	1.050898347	-1	free
221	220	229.096598	R	L	0.129778639	0.405478068	1.149294364	-1	free
222	221	230.0699314	L	R	0.148331001	0.477533472	1.43	-1	Pert: iw (L)
223	222	230.8816072	R	L	0.442098008	0.349733049	0.77	-1	action
224	223	231.8000476	L	R	0.468795822	0.310573717	0.810116196	0.057606167	target hit
225	224	232.7703358	R	L	0.19194444	0.437290219	1.120288213	-1	free

Figure 24: Example of "subject_X_cond_Y_run_Z_platformData.csv"

- “**subject_X_cond_Y_run_Z_gaitEvents.csv**” (time-stamped data with the gait events)

time	cop_z	cop_x	grf_y	imu1_LAngVel	imu1_LnAcc	imu2_RAngVel	imu2_RnAcc	imuGaitEvents_l_toe_off	imuGaitEvents_l_heel_strike	imuGaitEvents_r_toe_off	imuGaitEvents_r_heel_strike	copGaitEvents_l_toe_off	copGaitEvents_l_heel_strike	copGaitEvents_r_toe_off	copGaitEvents_r_heel_strike	copGaitEvents_l_toe_off_z	copGaitEvents_l_toe_off_x	copGaitEvents_l_heel_strike_z	copGaitEvents_l_heel_strike_x	copGaitEvents_r_toe_off_z	copGaitEvents_r_toe_off_x	copGaitEvents_r_heel_strike_z	copGaitEvents_r_heel_strike_x
0	-0.006066109	-0.161191036	684.980835	23.90243912	9.733993469	-0.853658557	9.455543176	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.055710578	-0.001951906	-0.164170479	688.9874268	23.47561073	9.610524331	-0.48780489	9.409794915	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
0.062540373	-0.001951906	-0.164170479	688.9874268	23.47561073	9.610524331	-0.48780489	9.409794915	0	0	0	0	0	0	0	1	0	0	0	0	0	0	-0.0061	-0.1642
0.065873707	-0.001951906	-0.164170479	688.9874268	23.47561073	9.610524331	-0.48780489	9.409794915	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.06920704	-0.000892248	-0.164820584	688.6192017	23.96341515	9.727299221	-0.609756112	9.481880812	0	0	0	0	1	0	0	0	-0.0009	-0.1642	0	0	0	0	0	0
0.072540373	-0.000892248	-0.164820584	688.6192017	23.96341515	9.727299221	-0.609756112	9.481880812	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.075873707	-0.000892248	-0.164820584	688.6192017	23.96341515	9.727299221	-0.609756112	9.481880812	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.07920704	-0.000892248	-0.164820584	688.6192017	23.96341515	9.727299221	-0.609756112	9.481880812	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.082540373	4.61E-05	-0.165478724	688.0999756	24.20731735	9.643717968	-1.036585331	9.444447271	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.085873707	4.61E-05	-0.165478724	688.0999756	24.20731735	9.643717968	-1.036585331	9.444447271	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.08920704	4.61E-05	-0.165478724	688.0999756	24.20731735	9.643717968	-1.036585331	9.444447271	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.092540373	4.61E-05	-0.165478724	688.0999756	24.20731735	9.643717968	-1.036585331	9.444447271	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.095873707	4.61E-05	-0.165478724	688.0999756	24.20731735	9.643717968	-1.036585331	9.444447271	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.09920704	0.0010032	-0.166188681	687.6776123	23.10975647	9.723781656	-0.609756112	9.42648654	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.102540373	0.0010032	-0.166188681	687.6776123	23.10975647	9.723781656	-0.609756112	9.42648654	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.105873707	0.0010032	-0.166188681	687.6776123	23.10975647	9.723781656	-0.609756112	9.42648654	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.10920704	0.0010032	-0.166188681	687.6776123	23.10975647	9.723781656	-0.609756112	9.42648654	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.112540373	0.002106445	-0.166998895	687.4247437	24.0853672	9.695191708	-0.426829278	9.494834955	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 25: Example of “subject_X_cond_Y_run_Z_gaitEvents.csv”

Before hitting the “TOGGLE PERTURBATION” button, the PI are labelled as “base”, meaning that the PI of the native gait are gathering. As soon as the “TOGGLE PERTURBATION” button is hit, the system goes to the state “free” and triggers visual cues. The label “free” determines unperturbed steps between two consecutive perturbations. When a visual cue is triggered, the system adds “Pert” label with the corresponding perturbation direction and a target step. For example, if visual cue in the forward-inward direction appeared for the left foot (light red ellipse), the message “Pert: fwiw (L)” was added to the “**subject_X_cond_Y_run_Z_platformData.csv**” file. The following step is labeled as “action”, meaning that the subject needs to step to the desired location. The next step contains one of the following messages: “target hit” or “target missed”, depending on whether the target was hit or not. Here, the minimum target error was calculated and labelled. Note that target is considered and labelled as hit if the target error is lower than 0.15 m.

6. Software Description

6.1. D-Flow application

D-Flow software runs the BeStable testbed with the application, which can be found in File?Open…?Browse to **D:\CAREN Resources\Projects\BeStable platform ver2\Applications\Bestable_v10.caren**

Note that the shortcut to “**Bestable_v10.caren**” is also placed on the PC desktop. Figure XXX shows its block diagram, where the important blocks are described in the following sections.

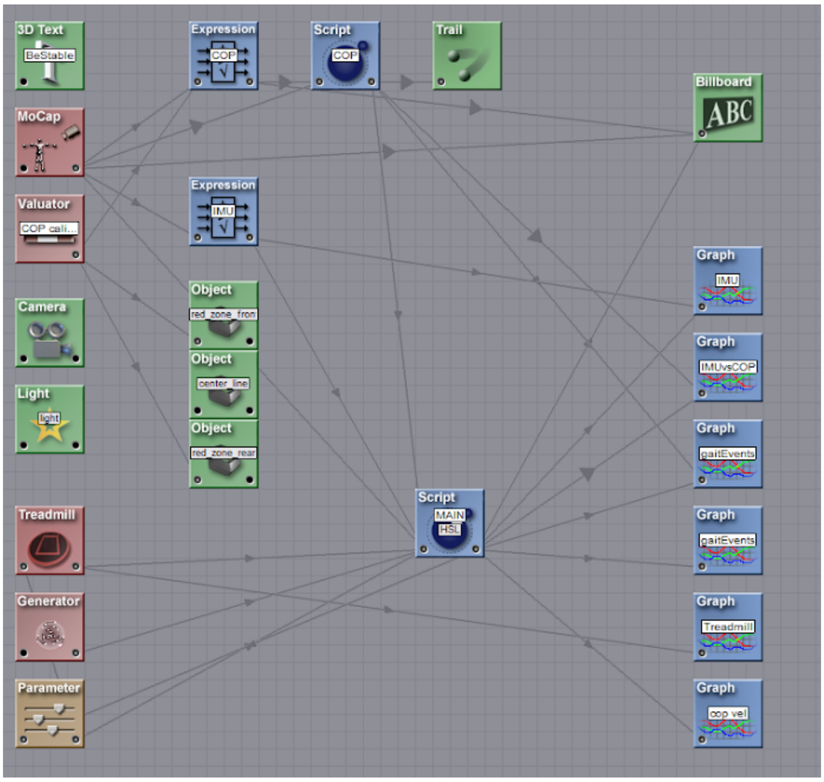


Figure 38: D-Flow application for the BeStable testbed

6.2. Main script block

The MAIN SCRIPT BLOCK does the following:

- imports external scripts,
- initializes all global variables (subject and protocol parameters from the Runtime console, COP, GRF, treadmill and IMU parameters, visualization objects, sounds),
- executes the state machine (presented in the D-Flow state machine section),
- write data to the output files (presented in the Recording data section),
- update gait events,
- compute stepping parameters.

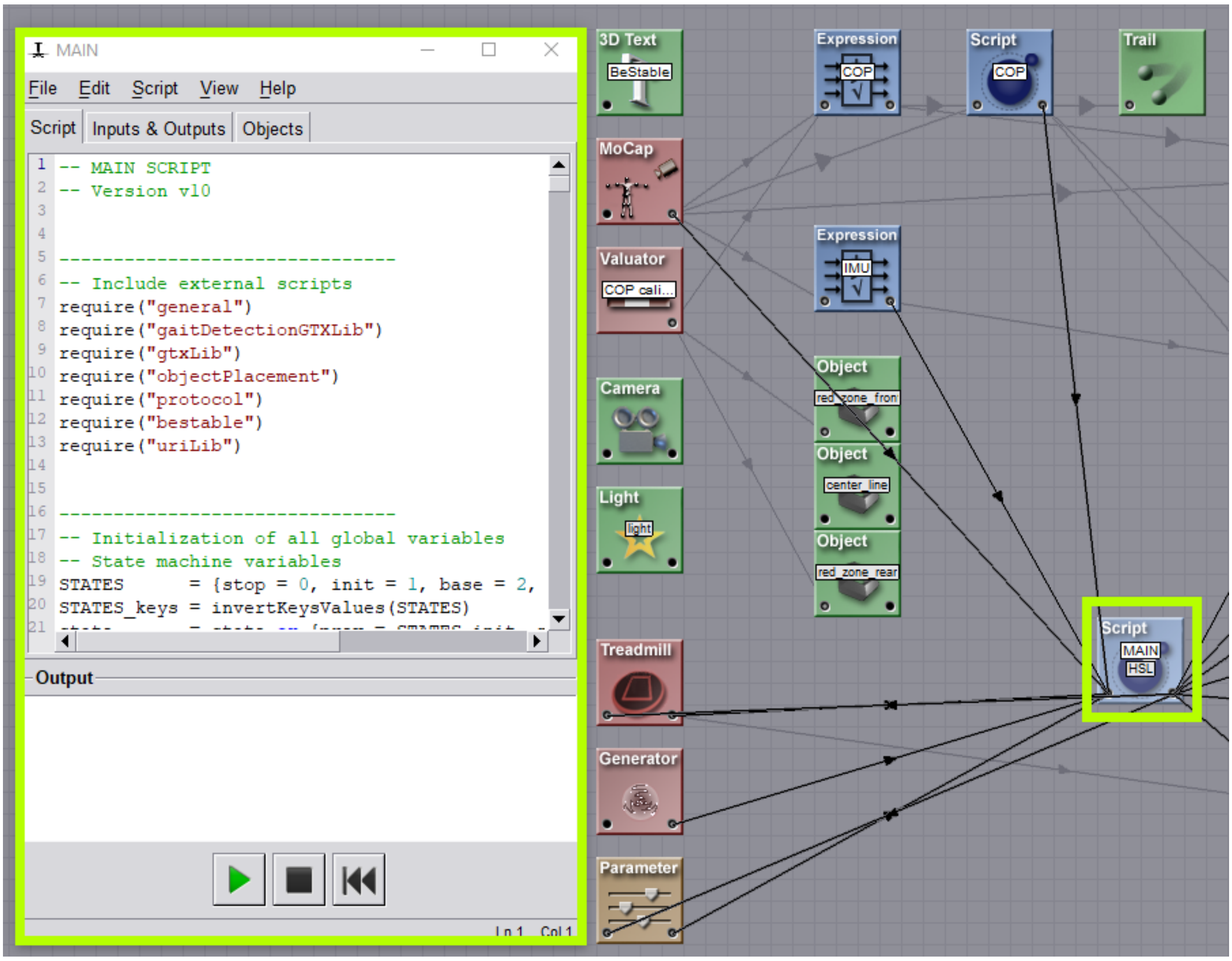


Figure 39: Main script block

6.3. COP related blocks

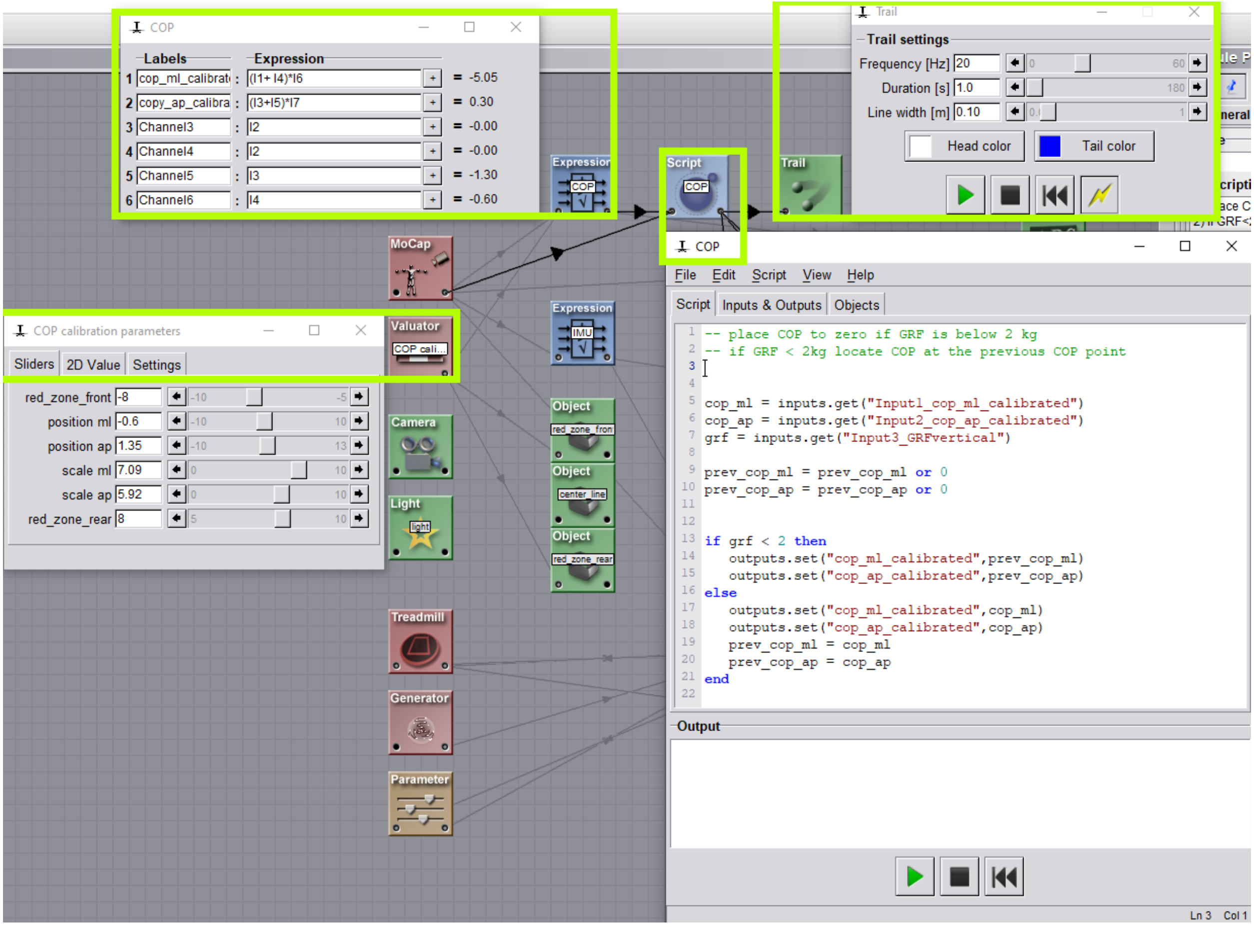


Figure 40: COP related blocks in the D-Flow application

The COP related blocks do the following:

- in the VALUATOR BLOCK the COP calibration parameters can be set (position ml, position ap, scale ml, scale ap),
- EXPRESSION BLOCK calculates the new COP based on the COP calibration parameters from the VALUATOR BLOCK,
- COP SCRIPT BLOCK locates COP at the previous COP point if ground reaction force is below 2 N,
- TRAIL BLOCK shows COP trail with the desired settings.

6.4. MoCap block

Although MoCap stands for motion capture data, in our system, we do not have any motion capture data. Instead, the module is used to load data from force plates and the Delsys system (EMG and IMU).

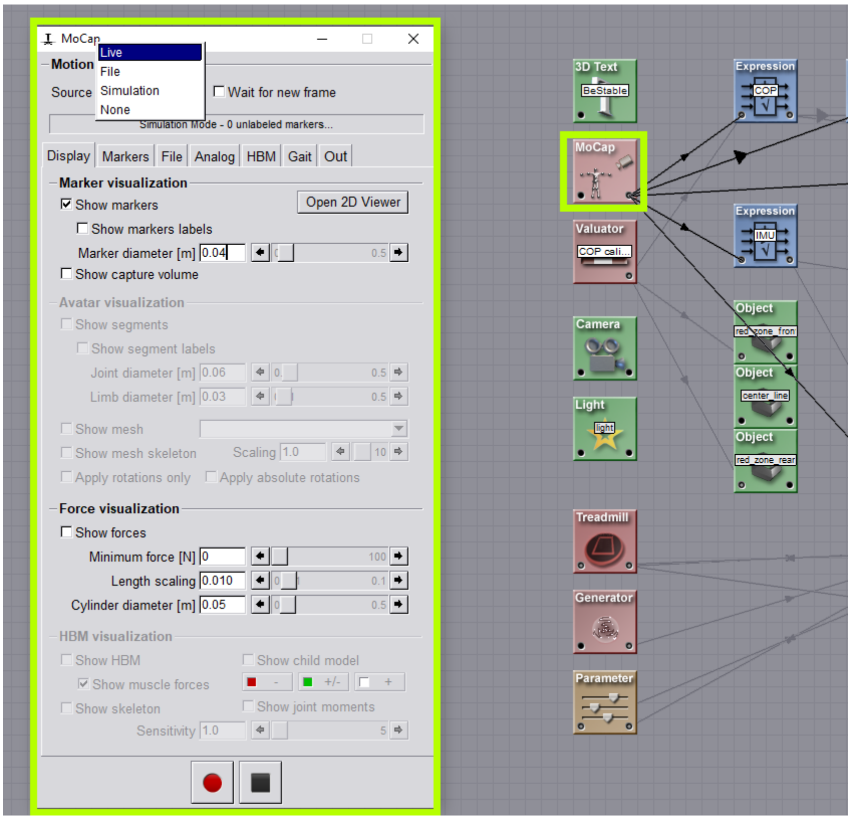


Figure 41: MoCap block

a. Open the GUI of the MoCap block by clicking on it. At the top of the window, make sure the source is chosen as “Live” (for real-time activities) and not “simulation”!

b. Go to the analog tab and go to the bottom and click “calibrate zero level” to calibrate the force plate.

c. In D-Flow, look at the lower right corner where you can see data from various channels. The force plate channels are easy to identify from their meaningful names. However, this is not the case with the EMG and IMU channels. The channels used for IMU based gait detection in D-Flow are as follows:

Reading	Output channel from MoCap Module
Left pitch angular velocity (gyroscope)	Channel 36.Anlg
Left X acceleration (accelerometer)	Channel 33.Anlg
Left Y acceleration (accelerometer)	Channel 34.Anlg
Left Z acceleration (accelerometer)	Channel 35.Anlg
Right pitch angular velocity (gyroscope)	Channel 45.Anlg
Right X acceleration (accelerometer)	Channel 42.Anlg
Right Y acceleration (accelerometer)	Channel 43.Anlg
Right Z acceleration (accelerometer)	Channel 44.Anlg

d. Verify that you see the data getting updated in the corresponding channels when you step on the force plate or move the IMUs around.

e. It’s a good practice to eliminate the noise in the force plate (at no load) by using a threshold filter of approximately 2 N.

f. Go to the out tab, under the “Channels to output”, you can select the required channels. In the connection editor, only those channels will be visible (otherwise, it will display the entire list of channels and that would unnecessarily make the log files heavy). See the channel description table for details.

Channels description table:

Sensor	Channel	Information
Force plate	FP1.CopX	Force plate center of pressure (distance along x axis)
	FP1.CopY	Not applicable (2D force plate)
	FP1.CopZ	Force plate center of pressure (distance along z axis)
	FP1.ForX	Not applicable (2D force plate)
	FP1.ForY	Vertical force
	FP1.ForZ	Not applicable (2D force plate)
EMG sensors (1-16)	Channel 1-16	Raw EMG data from individual sensors
EMG sensors (1-16)	Channel 17-32	Unfiltered EMG data, but scaled by a million (Because D-Flow is not able to show less than million volts)
IMU 1	Channel 33-35	Acc (X,Y,Z)
	Channel 36-38	Gyro (X,Y,Z)
	Channel 39-41	Mag (X,Y,Z)
IMU 2	Channel 42-50	Acc, Gyro, Mag
IMU 3	Channel 51-59	Acc, Gyro, Mag
…	…	
IMU 14	Channel 149-158	Acc, Gyro, Mag
IMU 15	Channel 159-167	Acc, Gyro, Mag
IMU 16	Channel 168-176	Acc, Gyro, Mag
EMG sensors (1-16)	Muscle1.EMG To Muscle16.EMG	Filtered EMG data

Force Plate Calibration

- Open D-Flow and load the BeStable application.
- Double click on the MoCap block.
- Make sure the ‘Motion Capture Source’ is set to ‘Live’ (see Fig. ??? above).
- Navigate to the ‘Analog’ tab.
- Make sure that no load is placed on the treadmill.
- Press on the button ‘Calibrate Zero Level’.
- Check that the system is successfully receiving force plate data by double clicking on the Graph module that has the tag ‘FP’ on its icon. Apply some force on the treadmill and check that the readings correspond to the applied load.

6.5. Treadmill block

Since the treadmill target speed is set in the Runtime console (shortcut F2), this block has no action on treadmill speed. However, maximum speed (set to 2 m/s) and the maximum acceleration/deceleration (set to 0.3 m/s2) can be adjusted.

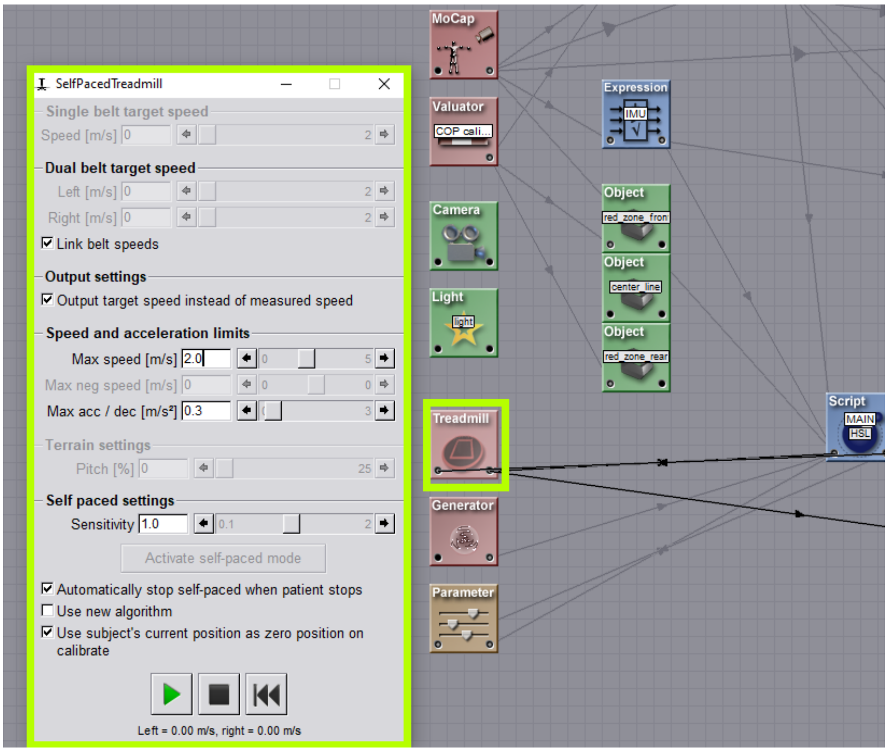


Figure 42: Treadmill block

6.6. Parameter block

In the Parameter block, settings for the GUI Runtime console (shortcut F2) are defined.

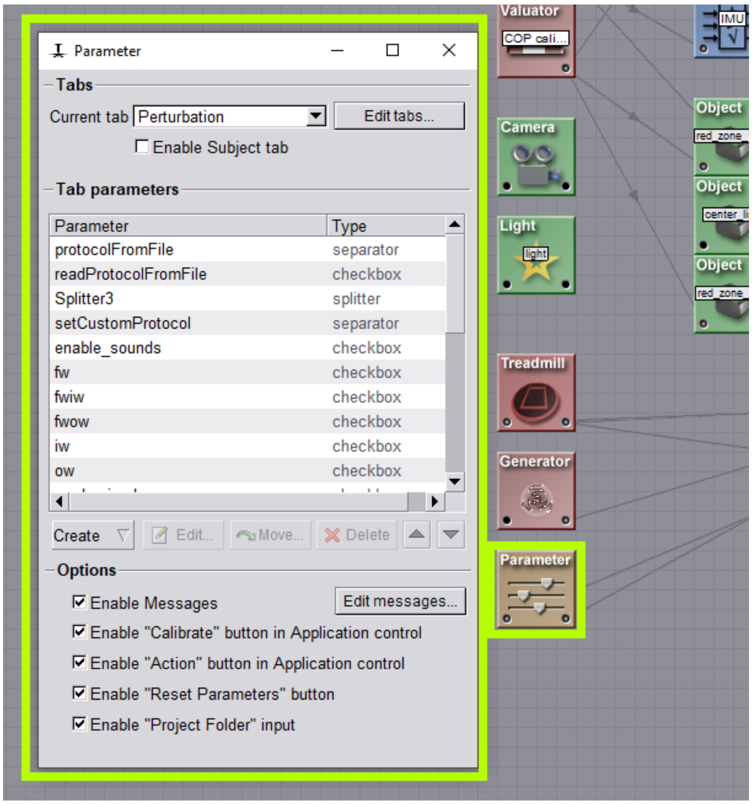


Figure 43: Parameter block

6.7. Camera block

Camera block is important to set the visualization view and locate the origin of the coordinate system to the desired position. By positioning the X, Y and Z axis of the camera, move the origin of the coordinate system to the center of the treadmill.

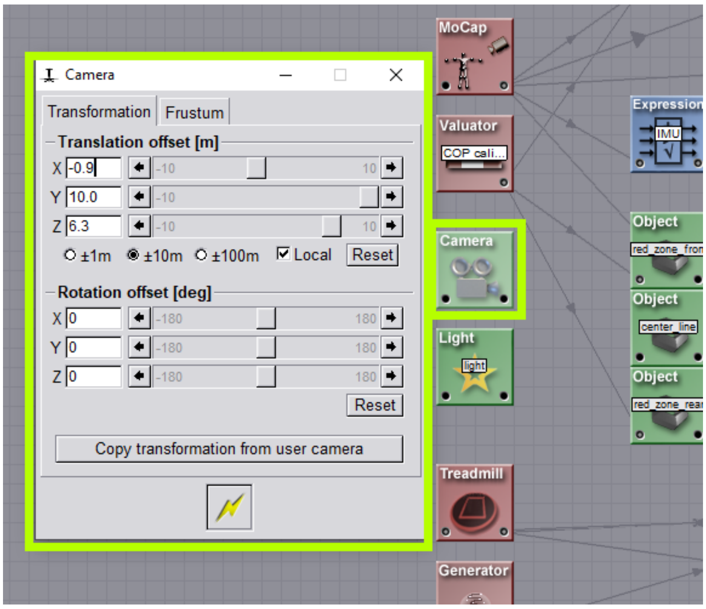


Figure 44: Camera block

6.8. D-Flow scripts

The D-Flow script (written in Lua programming language) follows the code structuring guideline given in the Lua tutorial from Motek. Based on this, the global variables are initialized at the beginning of the program. This is followed by the state machine (presented in the next section), which calls functions that are located in the following files, which are located in "D:\CAREN Resources\Projects\BeStable platform ver2\Scripts":

1) **bestable.lua** - miscellaneous functions for calculating moving average, etc.
2) **general.lua** - custom mathematical and logic functions
3) **objectPlacement.lua** - functions to check visual object visibility and place visual objects to the walking surface
4) **protocol.lua** - functions to set the protocol
5) **uriLib.lua** - functions and algorithm to detect gait events from the COP pattern, which is used for the calculation of the PI and triggering the perturbations
6) **gaitDetectionGTXLib.dll** - IMU gait detection library
7) **gtxLib.lua** - functions for IMU gait detection

6.9. D-Flow state machine

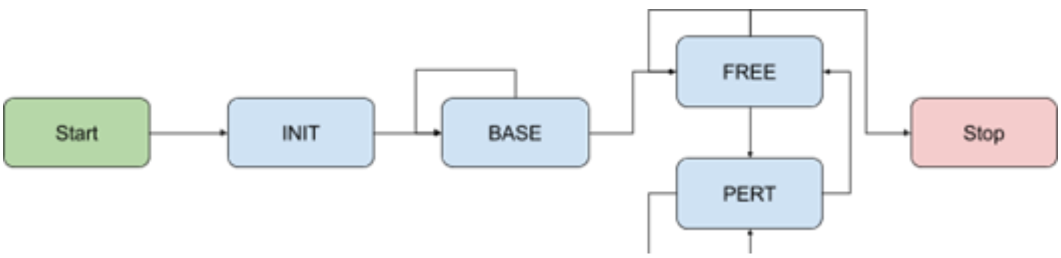


Figure 45: State machine diagram

Descriptions

- **Start**: The default state when D-Flow is started with the “Start” action button from the Runtime Console. This automatically transitions to the **Initialize** state.
- **Initialize**: Set default internal parameters. Once successful, this automatically transitions to the **Base** state.
- **Free**: Walk without targets shown
- **Pert**: A target is shown on the walking surface of the treadmill.
- Record the following parameters every step:
    - step number
    - time stamp
    - initial limb (anterior limb)
    - final limb (posterior limb)
    - step length,
    - step width,
    - step time (duration),
    - target error (after disappearing visual cue)
    - message of the step characteristic
- **Stop**: The default state when D-Flow is stopped with the “Stop” action button.

7. Appendix

7.1. Safety Harness Suspension

Here you can find some pictures on how the safety points are attached to the ceiling at URI. Please note that the two suspension points are not necessarily needed – this was only done to be able to place the treadmill centered under the lights.