BEAT – PROTOCOL AND PI MANUAL

Index

1. Motivation

The present document contains all the details related to the experimental protocol, performance indices and relative computational algorithms within the BEAT project.

2. Experimental protocols

A total of seven protocol can be performed through the use of the Roto.Bit^{3D}, designed within the BEAT project. The implemented protocols allow testing the performance of lower limb exoskeletons when subjects are required to perform gait and balance tests.

2.1. Protocol 1: Stepping on place – even surface

The aim of this protocol is the evaluation of the performance of lower limb exoskeleton when subjects perform walking task. Subject is required to step on the robotic platform for 60 s at the preferred cadence. The platform base is fixed in the neutral position, *i.e.* parallel to the floor. A sketch of the protocol is reported in Figure 1.

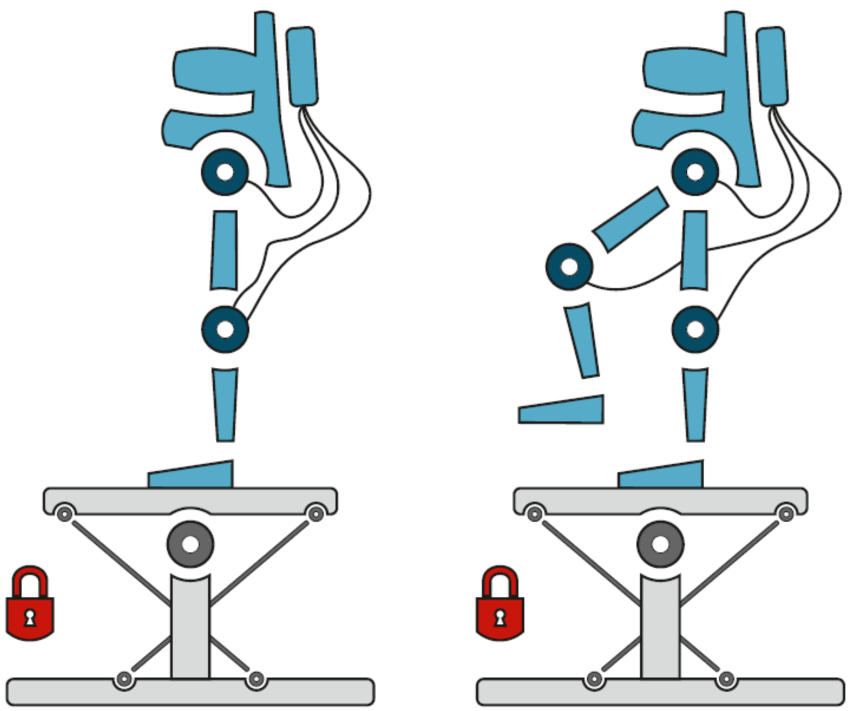

Figure 1 – Sketch of Protocol 1.

Protocol has to be performed both with and without wearing the exoskeleton in order to understand the effects induced by its presence. Subject has to be sensorized through sensor system for gathering lower limb joint angles and muscle activity. As regards the joint angles, opto-electronic system should be used; however inertial sensors can be alternatively selected as acquired sensor system. If opto-electronic system is used, the Plug-In-Gait protocol related to the lower limbs has to be followed for the marker placement [1]. Conversely, if IMUs will be used, please place one IMU on pelvis, one on thigh, one on shank and one on foot of each lower limb. For a correct extraction of joint angles from IMU data, it is suggested to perform before the protocol the functional calibration proposed by Palermo *et al.* [2], which is mandatory for the sensor alignment. As regards muscle activity, electrodes for surface electromyography have to be placed on the following muscles: tensor fasciae latae, rectus femoris, vastus lateralis, vastus medialis, peroneous longus, tibilias anterior, soleus, gluteus maximus, semitendinosus, biceps femoris, gastrocnemius lateralis, gastrocnemius medialis. For the electrode placement, it is suggested to follow the SENIAM guidelines [3]. It is worth highlighting that these are the suggested body segment and muscle to monitor during the execution of the task; however the related PI algorithms well work also with a different number of segments and muscles (for example, it could be impossible to sensorize some body segments/muscles due to the presence of the exoskeleton). For sake of clarity, it is necessary to have the same body segments and the same muscle when comparing the task performed with and without exoskeleton and also when comparing different subjects and/or different exoskeletons.

After the sensorization phase, subject has to go up the robotic platform and place his/her feet on the reference point signed on the platform base. Then, operator has to provide the correct instruction to the subject (Example: “Start to step on place at your preferred cadence until the stop”). Then, operator has to launch the platform software and select the appropriate protocol (for more details see Testbed_Manual). After the selection, the data acquisition will automatically start and stop after 60 s.

2.2. Protocol 2: Stepping on place – uneven surface

The aim of this protocol is the evaluation of the performance of lower limb exoskeleton when subjects perform walking task on an uneven surface. Subject is required to step on the robotic platform for 60 s at the preferred cadence. The platform base is free to move since an impedance control mode is set during this protocol. It means that subject feels a compliance base when stepping. A sketch of the protocol is reported in Figure 2.

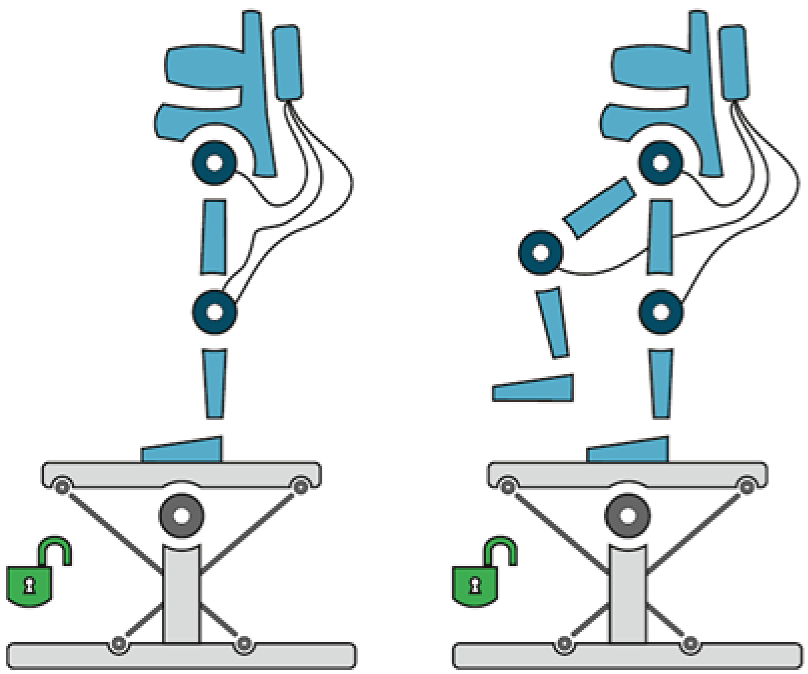

Figure 2 – Sketch of Protocol 2

Protocol has to be performed both with and without wearing the exoskeleton in order to understand the effects induced by its presence. Subject has to be sensorized through sensor system for gathering lower limb joint angles and muscle activity. As regards the joint angles, opto-electronic system should be used; however inertial sensors can be alternatively selected as acquired sensor system. If opto-electronic system is used, the Plug-In-Gait protocol related to the lower limbs has to be followed for the marker placement [1]. Conversely, if IMUs will be used, please place one IMU on pelvis, one on thigh, one on shank and one on foot of each lower limb. For a correct extraction of joint angles from IMU data, it is suggested to perform before the protocol the functional calibration proposed by Palermo *et al.* [2], which is mandatory for the sensor alignment. As regards muscle activity, electrodes for surface electromyography have to be placed on the following muscles: tensor fasciae latae, rectus femoris, vastus lateralis, vastus medialis, peroneous longus, tibilias anterior, soleus, gluteus maximus, semitendinosus, biceps femoris, gastrocnemius lateralis, gastrocnemius medialis. For the electrode placement, it is suggested to follow the SENIAM guidelines [3]. It is worth highlighting that these are the suggested body segment and muscle to monitor during the execution of the task; however the related PI algorithms well work also with a different number of segments and muscles (for example, it could be impossible to sensorize some body segments/muscles due to the presence of the exoskeleton). For sake of clarity, it is necessary to have the same body segments and the same muscle when comparing the task performed with and without exoskeleton and also when comparing different subjects and/or different exoskeletons.

After the sensorization phase, subject has to go up the robotic platform and place his/her feet on the reference point signed on the platform base. In order to guarantee the safety of the subject, he/she has to be required to wear the harness and operator has to attach it to the external structure of the platform. Then, operator has to provide the correct instruction to the subject (Example: "Start to step on place at your preferred cadence until the stop"). Then, operator has to launch the platform software and select the appropriate protocol (for more details see Testbed_Manual). Before starting the protocol, operator have the possibility to choose the compliance of the platform. In this case, it is suggested to always select the "medium" one; however if operator evaluates that this compliance is too easy or too difficult to administrate with a specific subject, the software offers the possibility to select also between "low" and "high" compliance. It is worth noticing that the selection of a different compliance cannot be neglected in successive analyses when comparing different subjects and different exoskeletons since it introduces different effects on the motor tasks. After the selection of the protocol and the compliance value, the data acquisition will automatically start and stop after 60 s.

2.3. Protocol 3: Static Balance – even surface

The aim of this protocol is the evaluation of the performance of lower limb exoskeleton when subjects perform static balance task on an even surface. Subject is required to maintain the equilibrium in the upright position on the robotic platform for 40 s. The platform base is fixed in the neutral position, *i.e.* parallel to the floor. The protocol has to be performed two time: the first with open eyes and the second with closed eyes. A sketch of the protocol is reported in Figure 3.

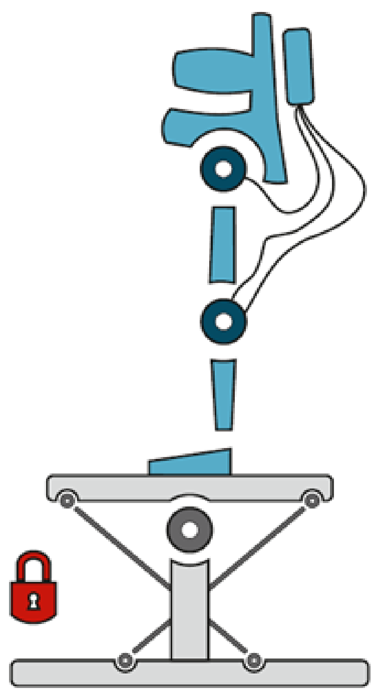

Figure 3 – Sketch of Protocol 3

Protocol has to be performed both with and without wearing the exoskeleton in order to understand the effects induced by its presence. No external sensor system are needed.

Subject has to go up the robotic platform and place his/her feet on the reference point signed on the platform base. Then, operator has to provide the correct instruction to the subject (Example: "Maintain the equilibrium with open or closed eyes"). Then, operator has to launch the platform software and select the appropriate protocol (for more details see Testbed_Manual). After the selection of the protocol and the compliance value, the data acquisition will automatically start and stop after 40 s.

2.4. Protocol 4: Static Balance – uneven surface

The aim of this protocol is the evaluation of the performance of lower limb exoskeleton when subjects perform static balance task on an even surface. Subject is required to maintain the equilibrium in the upright position on the robotic platform for 40 s. The platform base is free to move since an impedance control mode is set during this protocol. It means that subject feels a compliance base when a disequilibrium occurs. A sketch of the protocol is reported in Figure 4.

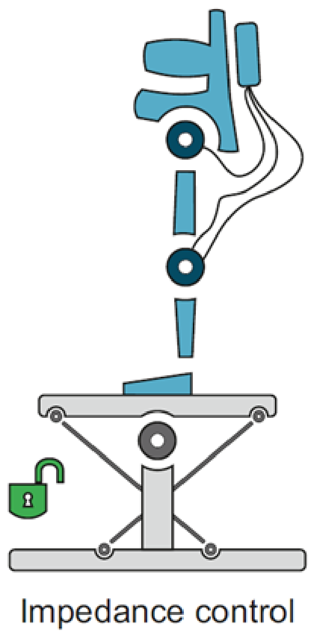

Figure 4 – Sketch of Protocol 4

Protocol has to be performed both with and without wearing the exoskeleton to understand the effects induced by its presence. No external sensor system are needed. To guarantee the safety, subject has to wear the harness and operator has to attach it to the external structure of the platform. Subject has to go up the robotic platform and place his/her feet on the reference point signed on the platform base. Then, operator has to provide the correct instruction to the subject (Example: “Maintain the equilibrium with open or closed eyes”). Then, operator has to launch the platform software and select the appropriate protocol (for more details see Testbed_Manual). Before starting the protocol, operator have the possibility to choose the compliance of the platform. In this case, it is suggested to always select the “medium” one; however if operator evaluates that this compliance is too easy or too difficult to administrate with a specific subject, the software offers the possibility to select also between “low” and “high” compliance. It is worth noticing that the selection of a different compliance cannot be neglected in successive analyses when comparing different subjects and different exoskeletons since it introduces different effects on the motor tasks. After the selection of the protocol and the compliance value, the data acquisition will automatically start and stop after 40 s.

2.5. Protocol 5: Step perturbation – even surface

The aim of this protocol is the evaluation of the performance of lower limb exoskeleton when subjects has to react to sudden step perturbation of the upright position. Subject is required to react to the perturbation avoiding any steps on the robotic platform with arms free to move. The platform base is controlled in position mode. Eight step perturbations are provided within the protocol, one per each direction according to the cardinal points. A sketch of the protocol is reported in Figure 5.

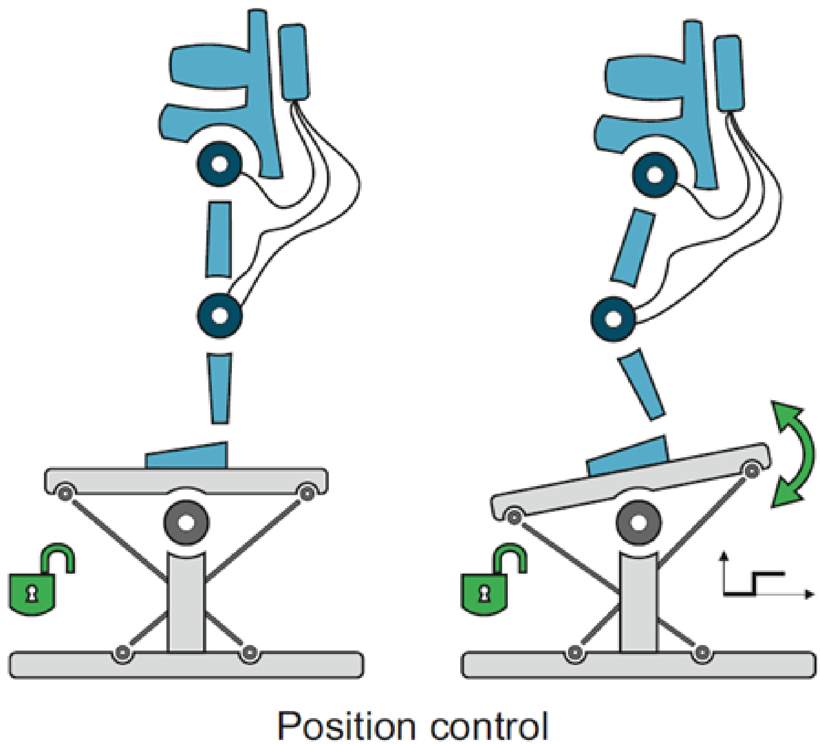

Figure 5 – Sketch of Protocol 5.

Protocol has to be performed both with and without wearing the exoskeleton in order to understand the effects induced by its presence. Subject has to be sensorized through sensor system for gathering lower limb joint angles. Opto-electronic system should be used; however inertial sensors can be alternatively selected as acquired sensor system. If opto-electronic system is used, the Plug-In-Gait protocol related to the lower limbs has to be followed for the marker placement [1]. Conversely, if IMUs will be used, please place one IMU on pelvis, one on thigh, one on shank and one on foot of each lower limb. For a correct extraction of joint angles from IMU data, it is suggested to perform before the protocol the functional calibration proposed by Palermo *et al.* [2], which is mandatory for the sensor alignment. It is worth highlighting that these are the suggested body segment to monitor during the execution of the task; however the related PI algorithms well work also with a different number of segments and muscles (for example, it could be impossible to sensorize some body segments/muscles due to the presence of the exoskeleton). For sake of clarity, it is necessary to have the same body segments when comparing the task performed with and without exoskeleton and also when comparing different subjects and/or different exoskeletons.

After the sensorization phase, subject has to go up the robotic platform and place his/her feet on the reference point signed on the platform base. To guarantee the safety, subject has to wear the harness and operator has to attach it to the external structure of the platform. Then, operator has to provide the correct instruction to the subject (Example: “Keep active to promptly react to the perturbation without performing any step”). Before the data acquisition, it is suggested to perform some familiarization tests. Then, operator has to launch the platform software and select the appropriate protocol (for more details see Testbed_Manual). Successively, operator has to select the amplitude and the velocity of the step perturbations. In this case, it is suggested to always select the “medium” one for both variables; however if operator evaluates that the amplitude and/or the velocity are too easy or too difficult to administrate with a specific subject, the software offers the possibility to select also between “low” and “high” for both variables. It is worth noticing that the selection of different values cannot be neglected in successive analyses when comparing different subjects and different exoskeletons since they introduce different effects on the motor tasks. After the selection, the data acquisition will automatically start and stop when all the perturbations are provided.

2.6. Protocol 6: Step perturbation – uneven surface

The aim of this protocol is the evaluation of the performance of lower limb exoskeleton when subjects has to react to sudden step perturbation of the upright position on a compliant base. Subject is required to react to the perturbation by bringing back the platform base on the natural position in 5 s; after this time period the platform automatically comes back to the neutral position. The platform base is controlled in impedance mode. Eight step perturbations are provided within the protocol, one per each direction according to the cardinal points. A sketch of the protocol is reported in Figure 6.

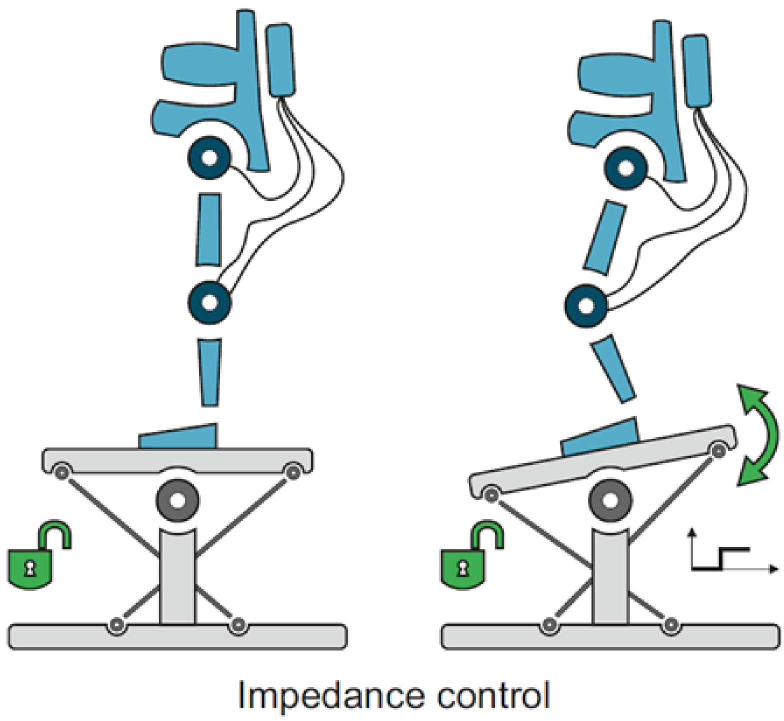

Figure 6 – Sketch of Protocol 6.

Protocol has to be performed both with and without wearing the exoskeleton in order to understand the effects induced by its presence. Subject has to be sensorized through sensor system for gathering lower limb joint angles. Opto-electronic system should be used; however inertial sensors can be alternatively selected as acquired sensor system. If opto-electronic system is used, the Plug-In-Gait protocol related to the lower limbs has to be followed for the marker placement [1]. Conversely, if IMUs will be used, please place one IMU on pelvis, one on thigh, one on shank and one on foot of each lower limb. For a correct extraction of joint angles from IMU data, it is suggested to perform before the protocol the functional calibration proposed by Palermo *et al.* [2], which is mandatory for the sensor alignment. It is worth highlighting that these are the suggested body segment to monitor during the execution of the task; however the related PI algorithms well work also with a different number of segments and muscles (for example, it could be impossible to sensorize some body segments/muscles due to the presence of the exoskeleton). For sake of clarity, it is necessary to have the same body segments when comparing the task performed with and without exoskeleton and also when comparing different subjects and/or different exoskeletons.

After the sensorization phase, subject has to go up the robotic platform and place his/her feet on the reference point signed on the platform base. To guarantee the safety, subject has to wear the harness and operator has to attach it to the external structure of the platform. Then, operator has to provide the correct instruction to the subject (Example: "Keep active to promptly react to the perturbation by bringing back the platform in the neutral position after the perturbation"). Before the data acquisition, it is suggested to perform some familiarization tests. Then, operator has to launch the platform software and select the appropriate protocol (for more details see Testbed_Manual). Successively, operator has to select the amplitude and the velocity of the step perturbations. In this case, it is suggested to always select the "medium" one for both variables; however if operator evaluates that the amplitude and/or the velocity are too easy or too difficult to administrate with a specific subject, the software offers the possibility to select also between "low" and "high" for both variables. It is worth noticing that the selection of different values cannot be neglected in successive analyses when comparing different subjects and different exoskeletons since they introduce different effects on the motor tasks. After the selection, the data acquisition will automatically start and stop when all the perturbations are provided.

2.7. Protocol 7: Sinusoidal perturbation – even surface

The aim of this protocol is the evaluation of the performance of lower limb exoskeleton when subjects has to react to sudden sinusoidal perturbation of the upright position. Subject is required to react to the perturbation avoiding any steps on the robotic platform with arms free to move. The platform base is controlled in position mode. Four sinusoidal perturbations are provided within the protocol, one per each direction: antero-posterior, medio-lateral, vertical and a mixed of the previous three. A sketch of the protocol is reported in Figure 7.

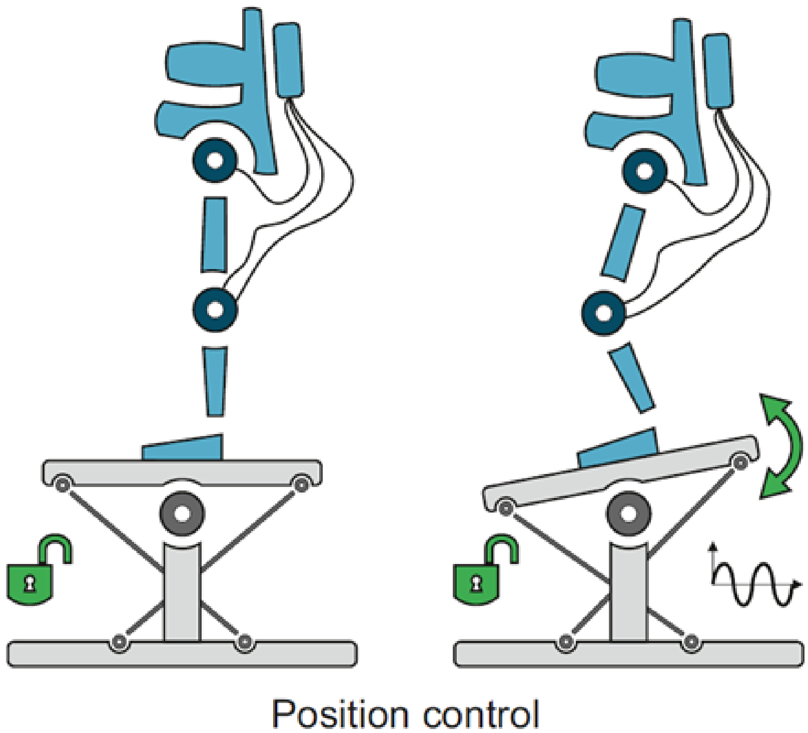

Figure 7 – Sketch of Protocol 7.

Protocol has to be performed both with and without wearing the exoskeleton in order to understand the effects induced by its presence. Subject has to be sensorized with inertial sensors. IMUs have to be placed on head, trunk and pelvis through the elastic belts. After the sensorization phase, subject has to go up the robotic platform and place his/her feet on the reference point signed on the platform base. To guarantee the safety, subject has to wear the harness and operator has to attach it to the external structure of the platform. Then, operator has to provide the correct instruction to the subject (Example: "Keep active to promptly react to the perturbation without performing any step"). Before the data acquisition, it is suggested to perform some familiarization tests. Then, operator has to launch the platform software and select the appropriate protocol (for more details see Testbed_Manual). Successively, operator has to select the amplitude and the frequency of the sinusoidal perturbations. In this case, it is suggested to always select the "medium" one for both variables; however if operator evaluates that the amplitude and/or the frequency are too easy or too difficult to administrate with a specific subject, the software offers the possibility to select also between “low” and “high” for both variables. It is worth noticing that the selection of different values cannot be neglected in successive analyses when comparing different subjects and different exoskeletons since they introduce different effects on the motor tasks. After the selection, the data acquisition will automatically start and stop when all the perturbations are provided.

3. Performance Indicators

A total of 16 performance indicators have been selected to evaluate the performance of the exoskeleton. Specifically, they can be divided into four main categories: kinematic, muscle activity, body stability, response to external perturbation.

3.1. Kinematic indicators

Three different kinematic indicators have been chosen.

3.1.1 Mean Range of Motion – mROM

This index represents the mean value of Range of Motion related to the examined lower limb joint angles. It is obtained as the difference between the maximum and minimum value of the angle within the same stride; then the average across strides is computed and selected as synthetic indices. A graphical example of the Range of Motion in a single stride for the knee angle is reported in Figure 8.

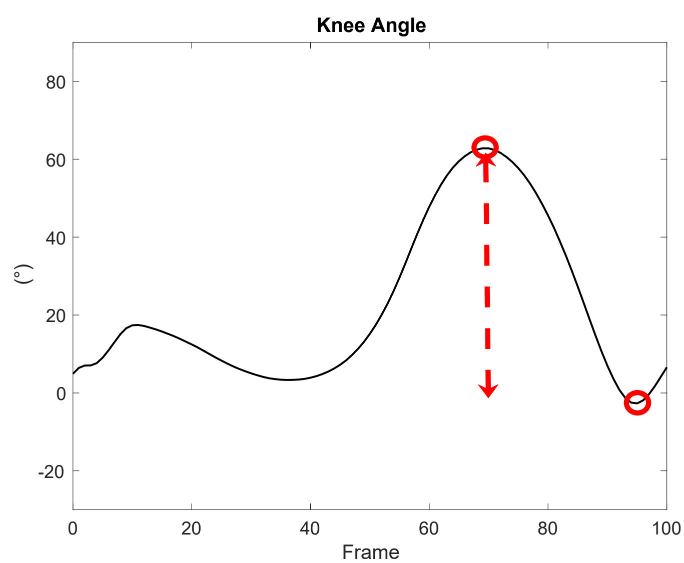

Figure 8 – Example of Range of Motion in a single stride

Obtained values should be compared with the ones reported in literature for the specific examined joint. Generally, smaller values indicate a reduction of the physiological movement of the examined joint.

The index is expressed in °. To obtain a global score across subject, the mean and standard deviation have to be computed. It is worth clarifying that this operation has scientific meaning only if the subjects have the same health status and wear the same exoskeleton.

For more details on the computation of the mROM, please see [4].

3.1.2 Coefficient of Variation - CoV

This index represents the ratio between the mean value of the Range of Motion and its standard deviation computed across all the performed strides. Greater value of the CoV indicate a greater variability of the kinematic.

The index is expressed in %. To obtain a global score across subject, the mean and standard deviation have to be computed. It is worth clarifying that this operation has scientific meaning only if the subjects have the same health status and wear the same exoskeleton.

For more details on the computation of CoV, please see [5].

3.1.3 Range of Motion in different perturbation directions – ROM_p

ROM_p represents the value of the range of motion related to each perturbation direction when step perturbation protocols have to be analyzed. ROM is computed as the difference between the maximum and minimum value of the examined joint angle in the same perturbation direction. Generally, smaller value of the ROM_p indicate a reduction of the physiological movement of the subject.

The index is expressed in %. To obtain a global score across subject, the mean and standard deviation have to be computed. It is worth clarifying that this operation has scientific meaning only if the subjects have the same health status and wear the same exoskeleton.

3.2. Muscle activity indicators – rNOS and lNOS

The number of muscle synergy, independently per each lower limb, has been selected as synthetic indices. For more details on the muscle synergy theory, please have a look to the following Figure 9 and see [6].

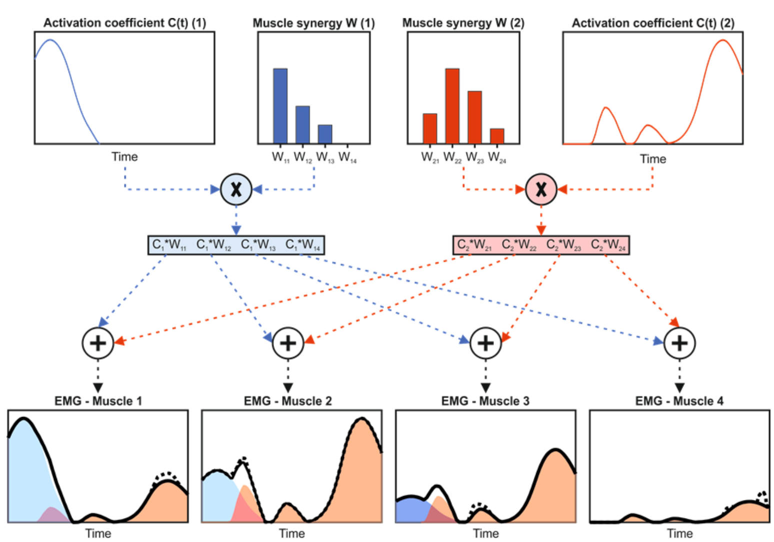

Figure 9 – Muscle synergy theory

The index is an adimensional scalar ranged from 1 to the number of examined muscles. Lower number of muscle synergies indicates an optimization of the muscle coordination performed by the Central Nervous System, when tasks are performed by healthy subject, or the impossibility to active all the muscle in case of pathological subjects. To obtain a global score across subject, the median and mode have to be computed. It is worth clarifying that this operation has scientific meaning only if the subjects have the same health status and wear the same exoskeleton.

3.3. Body stability indicators

Six different body stability indicators have been selected.

3.3.1 Path length of the Centre of Pressure – PL

This index represents the distance covered by the centre of pressure (CoP) in the plane. The computation of PL is performed by the following equation 1:

$$PL = \sum_{n=1}^{N-1} [(AP[n+1] - AP[n])^2 + (ML[n+1] - ML[n])^2]^{1/2} \quad (1)$$

where AP and ML represent the antero-posterior and medio-lateral components, respectively and n the number of point of the CoP during the task. A graphical example of the CoP trajectory is reported in Figure 10.

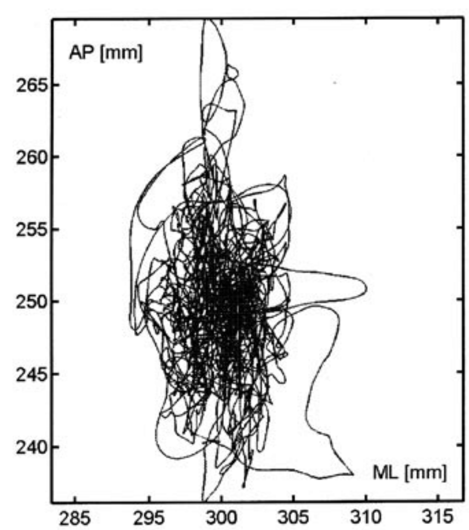

Figure 10 - Example of CoP trajectory in the plane

The index is expressed in m and it is a scalar value. Greater value of PL indicates greater instability of the subjects. To obtain a global score across subject, mean and standard deviation have to be computed. It is worth clarifying that this operation has scientific meaning only if the subjects have the same health status and wear the same exoskeleton.

If user want to obtain a global score that takes into account the two visual conditions, i.e. open and closed eyes, the Romberg Index has to be computed as the ratio between the index related to the closed eyes task and the one related to the open eye. Index equal to 1 indicate a perfect agreement between the two conditions. Index lower than 1 indicate an increase of the instability when performing the task with closed eyes.

For more details on the computation of PL and Romberg Index, please see [7].

3.3.2 Path length of the Centre of Pressure in antero-posterior direction – PL_{AP}

This index represents the distance covered by the CoP only considering the antero-posterior direction. The used equation is the same of Eq.1 by considering equal to zero the ML components.

The index is expressed in m and it is a scalar value. Greater value of PL_{AP} indicates greater instability of the subjects in antero-posterior direction. To obtain a global score across subject, the median and mode have to be computed. It is worth clarifying that this operation has scientific meaning only if the subjects have the same health status and wear the same exoskeleton.

If user want to obtain a global score that takes into account the two visual conditions, i.e. open and closed eyes, the Romberg Index has to be computed as the ratio between the index related to the closed eyes task and the one related to the open eye. Index equal to 1 indicate a perfect agreement between the two conditions. Index lower than 1 indicate an increase of the instability when performing the task with closed eyes.

3.3.3 Path length of the Centre of Pressure in antero-posterior direction – PL_{ML}

This index represents the distance covered by the CoP only considering the medio-lateral direction. The used equation is the same of Eq.1 by considering equal to zero the AP components.

The index is expressed in m and it is a scalar value. Greater value of PL_{ML} indicates greater instability of the subjects in medio-lateral direction. To obtain a global score across subject, mean and standard deviation have to be computed. It is worth clarifying that this operation has scientific meaning only if the subjects have the same health status and wear the same exoskeleton.

If user want to obtain a global score that takes into account the two visual conditions, i.e. open and closed eyes, the Romberg Index has to be computed as the ratio between the index related to the closed eyes task and the one related to the open eye. Index equal to 1 indicate a perfect agreement between the two conditions. Index lower than 1 indicate an increase of the instability when performing the task with closed eyes.

3.3.5 Area of the confidence ellipse – EA

This index represents the area of the minimum confidence ellipse containing the 95% of the points of the CoP trajectory in the plane. The computation of the EA is performed through the Equation 2:

$$EA = 2\pi F_{.05[2,N-2]}[s_{AP}^2 s_{ML}^2 - s_{APML}^2]^{1/2} \qquad (2)$$

where F_(.05[2,N-2]) is the F statistic at a 95% confidence level for a bivariate distribution with N points. s_AP^2 and s_ML^2 are the variance of the AP and ML , and s_APML^2 is the covariance. A graphical example of the EA is reported in Figure 11.

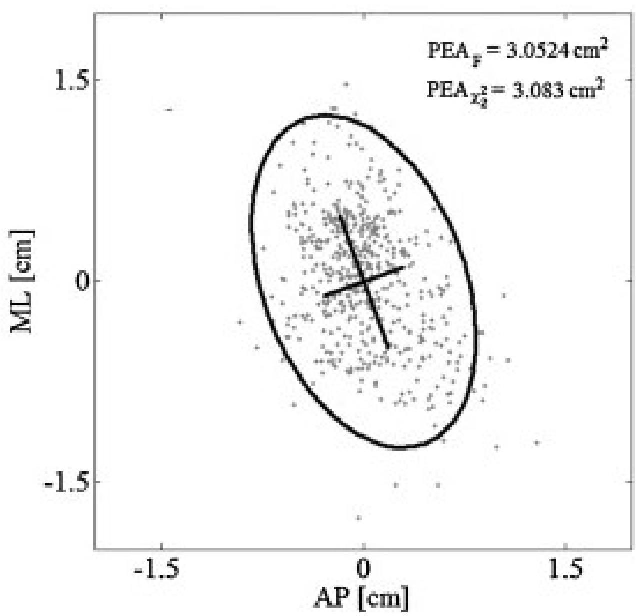

Figure 11 – Example of the confidence ellipse drawn on CoP trajectory

The index is expressed in m^2 and it is a scalar value. Greater value of EA indicates greater instability of the subjects. To obtain a global score across subject, mean and standard deviation have to be computed. It is worth clarifying that this operation has scientific meaning only if the subjects have the same health status and wear the same exoskeleton.

If user want to obtain a global score that takes into account the two visual conditions, i.e. open and closed eyes, the Romberg Index has to be computed as the ratio between the index related to the closed eyes task and the one related to the open eye. Index equal to 1 indicate a perfect agreement between the two conditions. Index lower than 1 indicate an increase of the instability when performing the task with closed eyes.

For more details on the computation of PL and Romberg Index, please see [7].

3.3.5 Path Length of the Centre of Pressure after perturbation – PL_p

This index is the same of the one reported in the subparagraph 3.3.1 with the difference that it is computed according each direction of the imposed perturbation. The same meaning and the same steps for the global score is suggested.

No Romberg Index can be computed since perturbation protocols are performed only with open eyes.

3.3.1 Area of the confidence ellipse after perturbation – EA_p

This index is the same of the one reported in the subparagraph 3.3.4 with the difference that it is computed according each direction of the imposed perturbation. The same meaning and the same steps for the global score is suggested.

No Romberg Index can be computed since perturbation protocols are performed only with open eyes.

3.4. Response to perturbations indicators

Five different performance indicators have been selected.

3.4.1 Platform angle overshoot – OS

This index represents the overshoot of the platform angles after subject's reaction under step perturbation. It is computed as the difference between the maximum value of the angle platform and the value of the imposed perturbation. It is computed for each of the eight step perturbation directions. A graphical example of the OS is reported in Figure 12.

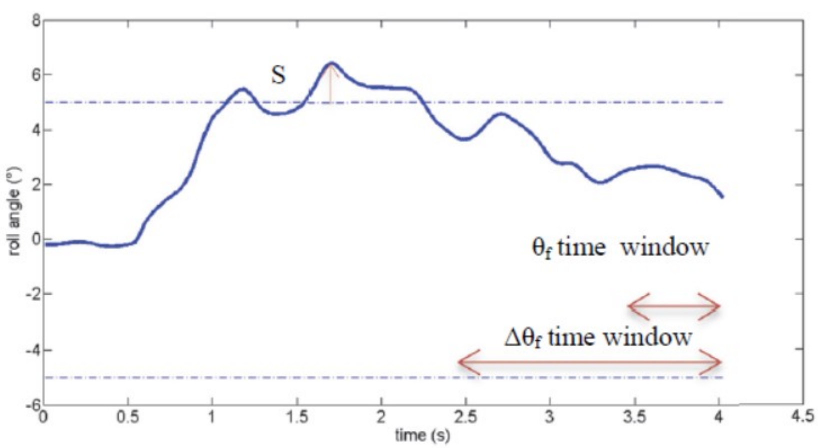

Figure 12 - Example of indicators of the step perturbations. Dotted line represent the imposed perturbation, blue line the platform angle.

This index is expressed in °. Lower value of OS indicates a better anticipatory postural adjustment of the subjects. To obtain a global score across subject, mean and standard deviation have to be computed per each direction. It is worth clarifying that this operation has scientific meaning only if the subjects have the same health status and wear the same exoskeleton.

For more details on the computation of OS, please see [8].

3.4.2 Final value of the platform angle – theta_f

This index represents the final value of the platform angle after subject's reaction to the step perturbation. It is computed as the mean value of the platform angle of the last 50 samples for each step perturbation direction. See Figure 12 for a graphical example of this index.

This index is expressed in °. Value of theta_f close to zero indicates a perfect capability of the subject to bring back the platform in the neutral position. To obtain a global score across subject, mean and standard deviation have to be computed per each direction. It is worth clarifying that this operation has scientific meaning only if the subjects have the same health status and wear the same exoskeleton.

For more details on the computation of OS, please see [8].

3.4.3 Range of motion of the platform angle – delta_theta

This index represents the range of motion of the platform angle after subject's reaction to the step perturbation. It is computed as the difference between the maximum and the minimum value of the platform angle in the last 1.5 s of the task for each step perturbation direction. See Figure 12 for a graphical example of this index.

This index is expressed in °. Lower value of delta_theta indicates a greater stability after the perturbation direction. To obtain a global score across subject, mean and standard deviation have to be computed per each direction. It is worth clarifying that this operation has scientific meaning only if the subjects have the same health status and wear the same exoskeleton.

For more details on the computation of OS, please see [8].

3.4.5 Gain index – G

This index is computed through a Fourier analysis. Specifically, the following steps are considered:

a. Computation of the power spectrum of the imposed sinusoidal perturbation (a)
b. Computation of the power spectrum of the examined body segment angle (b)
c. Identification of the main frequency of the power spectrum (a)
d. Computation of the amplitude of the power spectrum (a) in correspondence of the main frequency identified in (c)

e. Computation of the amplitude of the power spectrum (b) in correspondence of the main frequency identified in (c)
f. Ratio between the two amplitude (d/e)

Thus, the index represents the ratio between the amplitude of the sinusoidal perturbation and the amplitude of the body segment angle both computed at the main frequency of the sinusoidal perturbation spectrum. A graphical representation of the two signal in time and frequency domain is reported in Figure 13.

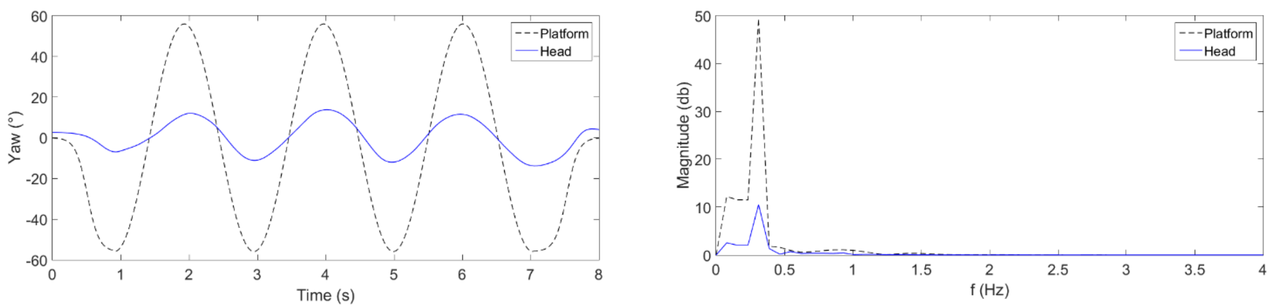

Figure 13 – Example of sinusoidal perturbation imposed by the platform (dotted line) and head angle (blue line) on the left and related power spectrum in the right.

The index is expressed as % and it is computed per each perturbation direction. Only the body segment angles in transversal plane are examined. G value close to 100 % indicates that the examined segment is in perfect agreement with the perturbation. To obtain a global score across subject, mean and standard deviation have to be computed per each direction. It is worth clarifying that this operation has scientific meaning only if the subjects have the same health status and wear the same exoskeleton.

For more details on the computation of G, please see [9].

3.5.5 Phase shift – phi

This index is computed through a Fourier analysis. Specifically, the following steps are considered:

a. Computation of the phase as function of the frequency of the imposed sinusoidal perturbation (a)
b. Computation of the phase as function of the frequency of the examined body segment angle (b)
c. Identification of the main frequency of the power spectrum (a)
d. Computation of the phase of the spectrum (a) in correspondence of the main frequency identified in (c)
e. Computation of the phase of the spectrum (b) in correspondence of the main frequency identified in (c)
f. Difference between the two identified phase value (d – e)

Thus, the index represents the difference between the phase of the sinusoidal perturbation and the amplitude of the body segment angle both computed at the main frequency of the sinusoidal perturbation spectrum.

The index is expressed in ° and it is computed per each perturbation direction. Only the body segment angles in transversal plane are examined. Phi 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). To obtain a global score across subject, mean and standard deviation have to be computed per each direction. It is worth clarifying that this operation has scientific meaning only if the subjects have the same health status and wear the same exoskeleton.

For more details on the computation of phi, please see [9].

For details related to the PI algorithms please see the READ ME file in the git repository at the following link https://github.com/aremazeilles/beat_routine.

In order to summarize all the selected performance indicators, in the following Table 1 all the PI as function of the protocol in which they can be computed are reported.

Table 1 – Performance indicators computable per each protocol. X indicates the possibility to compute the specific PI in that protocol.

Protocol	mROM	CoV	ROM_p	rNOS	lNOS	PL	PL$_{AP}$	PL$_{ML}$	EA	PL_p	EA_p	OS	theta_f	delta_theta	G	phi
1	x	x		x	x											
2	x	x		x	x	x	x	x	x							
3						x	x	x	x							
4						x	x	x	x							
5			x							x	x					
6			x							x	x	x	x	x		
7										x	x				x	x

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