Being safe around collaborative and versatile robots in shared spaces

Protocol

Test Dynamic stability for Weight support systems

(WSU-DYS-1)

The purpose of this protocol is to test the skill “dynamic stability” of (mobile) weight support systems (with gait following function) type RACA robots* by measurement. Its scope is limited to weight support systems in indoor applications. In this context, the objective is to protect users and bystanders from injuries caused by tilting of the weight support system. The validation of this protocol requires that the reader has access to an inclinometer, a winch and a suitable 1D force sensor for tension force measurements.

Readiness Level	Description
7	Protocol is published over the toolkit, under evaluation, and open for community feedback.

COVR is a community effort and values any honest feedback to our services. Please feel free to express your opinion about this protocol. The feedback form is only one click away. Thanks for making COVR even better!

Disclaimer: This protocol reflects the current and collectively developed state of the art in the validation of a specific safety skill for a collaborative robot. However, you may have to adapt the described validation procedure to be feasible for your particular application, circumstances and applicable regulations. Neither the COVR project consortium as a whole nor any individual partner of the consortium takes, therefore, any responsibility for the correctness and completeness of the validation procedure described here.

Grant agreement no. 779966
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CONTENTS

1 Introduction

The purpose of this protocol is to test the dynamic stability for a RACA robot* that provides a (partial) weight support system with gait following function. We assume a scenario where the RACA robot* is supporting a human subject, where the human is suspended under the support system via a harness. Under certain circumstances the RACA robot* may tip over and can cause injury to either the suspended human subject or surrounding persons. The goal of the protocol is to validate foreseeable events do not lead to dynamic instability.

Figure 1: Left: example of use situation, with movement direction (A), the lateral roll (B) and the anterior posterior pitch (C); Right: concept of testing setup

1.1 Scope and limitation

This protocol is specifically limited to the following profile:

Skill	Maintain Dynamic Stability
System	Weight support system (with gait following function)
Sub-System	N.A.
Domain	Healthcare
Conditions	Inclination of the floor, floor surface material
Measurement Device(s)	Inclinometer, dummy subject, 1D force sensor, winch

⚠	**Warning**
	This protocol supports users only to validate the effectiveness of the skill listed in the profile above. The skill should be a technical measure for the robot system to mitigate the risk of one potentially hazardous situation as identified in the mandatory risk assessment. Consequently, the risk assessment must be done before using this protocol.

1.2 Definitions and Terms

Gait following function(source: local to the document)

A function that causes a RACA robot* to follow the walking movements of a user

Pitch (source: local to the document)

Rotation along an axis running from side to side of the platform as shown in Figure 2. We assume positive angle value for clockwise rotations and negative otherwise. An angle value of 0 means no rotation.

RACA robot (source: IEC 80601-2-78:2019 – clause 201.3.212)

Medical robot intended to perform Rehabilitation, Assessment, Compensation and Alleviation robot, comprising an actuated applied part.

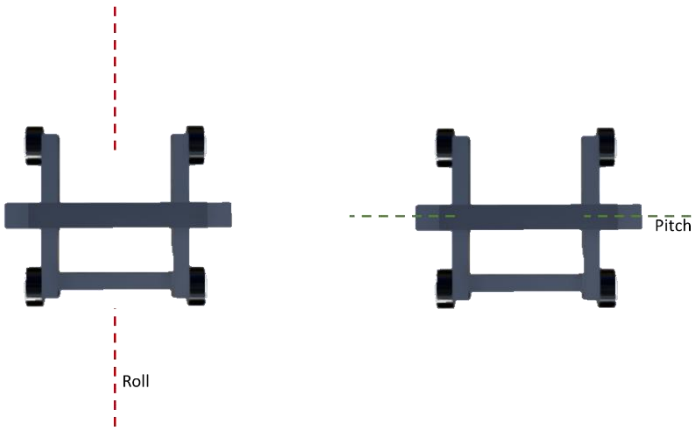

Figure 2: Definition of the terms pitch and roll with respect to the geometry of the robot.

Roll (source: local to the document)

Rotation along an axis running from front to the back of the platform as shown in Figure 2. We assume positive angle value for clockwise rotations and negative otherwise. An angle value of 0 means no rotation.

S.F.C. / Single fault condition (source: IEC 60601-1 definition 3.116)

A condition of Medical Electrical equipment in which a single means for reducing a risk is defective or a single abnormal condition is present

Weight support system (source: local to the document)

Body-weight support-type RACA ROBOT, optionally equipped with gait following function

2 Concept and Objectives

The risk assessment specifies which hazardous situations the protocol user must validate by test and whether the applied safety skill mitigates the risk effectively. The RACA robot* is assumed to be in certain state before the hazardous situation can occur (see section 3.1).

The validation process consists of creating a movement of the supported load and to validate by measurements that stability is maintained.

2.1 Hazardous Situations

A hazardous situation may occur when the RACA robot* becomes unstable. Potentially this may lead to a decreased performance in the support of the user, or even to cause the user to fall by pulling that user in a specific direction. Toppling over of the RACA robot* may then even lead to additional damage to the user.

Another hazardous situation may occur when the user stumbles and falls into the support structure, causing the system to tumble over.

A third hazardous situation may occur when, if the user is fully suspended by the RACA robot* and the COM of the user is moved significantly. The RACA robot* may try to compensate for these motions and possibly initiates an oscillation causing discomfort for the user.

2.2 Target Behavior and Metrics of the Safety Skill

The target behavior of the skill to be validated is to maintain stability for the RACA robot* and therefore maintain stable support to the user

For validating the robot skill dynamic stability, the *output target* (dynamic measurements) are the values

- $roll(t)$
- $pitch(t)$

where t denotes the time parameter. In other words, a timeseries of roll and pitch inclinations is captured. Notice that positive values denote clockwise rotations and negative counterclockwise rotations. The evaluation criteria given later will ignore the sign.

The values for the *target metric* (static measurements - expected limits) should be selected through the risk assessment and technical specification of the mobile platform. For this validation protocol, the target metric is:

- $roll_{stability}$ where $0° < roll_{stability} < 10°$
- $pitch_{stability}$ where $0° < pitch_{stability} < 10°$.

The max $roll_{stability}$ and $pitch_{stability}$ values can be specified differently by the manufacturer.

Pass criteria

The test is passed if

$$SF \max(|roll(t)|) < roll_{stability} \ and$$
$$SF \max(|pitch(t)|) < pitch_{stability}$$

Where $\max(|\ldots|)$ denotes the maximum absolute of the roll and pitch angles measured over time and the SF is a safety factor ($SF \geq 1$). In other words, the system passes the test in case the measured dynamic values stay within the static stability limits to a tolerance of a safety factor.

Please report the values of the target metric for each test using the form in the Annex.

3 Conditions

In case the conditions under which the hazardous situation may occur can change, the user of this protocol shall develop a test plan containing all their reasonable and relevant combinations. The user must test the applied skill for each combination of this list. Therefore, it is important to know the conditions with the most significant influence on the target metrics. Please report all conditions, represented by values, for each test using the form in Annex.

3.1 System

The term *system* refers to a robot system that consists of the:

- Weight support system
- Payload handled by the weight support system

System

Weight support system	
Manufacturer	The WeightSupport Company
Model	WSup 10
Control Software Version	Safety Package v 3.2
Payload	
Description	Dummy in harness
Mass [kg]	1.2 x 135 kg or, when another maximum allowed payload is specified by the manufacturer, take 1.2 x maximum allowed payload
Picture of the payload	…insert picture…
Entire system	
Picture of the complete system	…insert picture…

3.2 Environment

The environment in which the experiments take place will have influencing factors like:

1. Inclination of the floor
2. Surface of the floor
3. Velocity of movement
4. Turning with a small radius
5. Sudden positive of negative accelerations (either programmatically of by emergency stops).

3.3 Miscellaneous

The stability of the weight support system may also be influenced by:

1. Balance loss by the user, possibly causing sudden accelerations in the system
2. Single fault condition (S.F.C.) in the implementation of the safety skill

4 Test Setup

4.1 Equipment [former 4.2 Sensing devices]

An inclinometer is used to validate the skill. This inclinometer must support recording of roll and pitch axis over time.

Table 1: Requirements for the force sensor

	Minimum	Recommended
Calibrated range	0 – 200 N	0 – 500 N
Accuracy	1 N	1 N
Sampling rate	100Hz	100Hz

Table 2: Requirements for the inclinometer

	Minimum	Recommended
Number of axes	2 (roll and pitch)	2 (roll and pitch)
Calibrated range	$-60 \dots 60°$	$-60 \dots 60°$
Accuracy	$\pm 1°$	$\pm 1°$
Sampling rate	100 Hz	100 Hz

Use the form in Annex A to report the capabilities of the sensor used for the validation.

Example: Sensors

Feature	Inclinometer
Manufacturer and type	Sensor Company, PE 1000
Serial number	SN2021-0001
Number of axis	2
Calibrated range	$\pm 60°$
Accuracy	$\pm 1°$
Sampling rate	1000 Hz

For mimicking a user a dummy shall be used. This dummy is mainly a weight of 150kg (as described in IEC 60601-1), unless otherwise specified by the manufacturer

4.2 Method

The force sensor should be mounted in the connection between the dummy and the winch and is used to measure and control the forces applied using the winch.

The inclinometer should be mounted to the weight support system prior to the tests and be initialized on a leveled surface.

Since expected velocities of the weight support system are low, the tests can be performed using a semi static approach, where forces and required motions will be applied on either the weight support system or on the weight suspended by the weight support system.

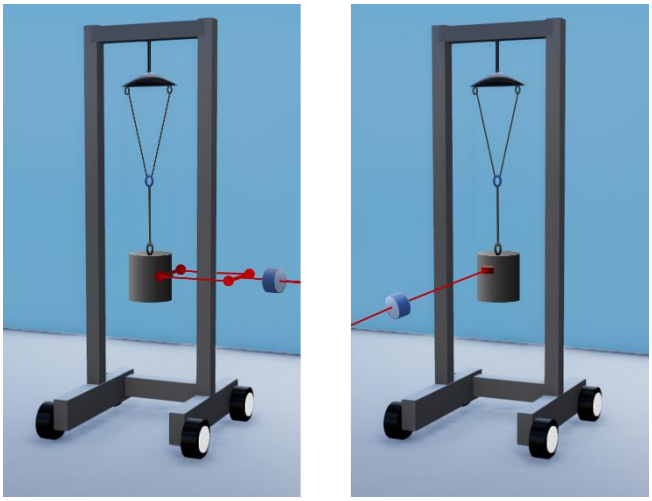

Figure 3: General structure of an appropriate test arrangement

A dummy, consisting of a weight with additional padding on the outside, shall be used to mimic the user. This dummy shall be covered with a padding material, to protect the weight support system from minor damage during the tests. The dummy shall be kept at a height of 1 m above the floor surface, representing the height of the COM of a user. To mimic a worst case situation the dummy shall be fully supported by the weight support system.

For protection of the weight support system, should the weight support system topple over during the validation tests, either a solid frame with padding can be put around the test location during the semi-static tests or a crane like mechanism can be used to protect the weight support system for fully falling over.

Validation of the safety skill is done by executing five consecutive tests, in four semi static situations and one dynamic situation:

Test 1

First test is to mimic a fall of a user into the support structure, by pulling the weight over to one side into the support structure (when possible) and keeping it pushing against the structure with a force of 10% of the weight of the dummy, mimicking a user leaning sideways into the support structure. This test only needs to be executed when width of the support structure is <= 90 cm.

Test 2

A second test is to mimic the a (nearly) falling user after an emergency stop by pulling the dummy forward and keeping it at a fixed spatial location. This test shall be executed both without and (if possible) with the implemented gait following function (or other movement function) enabled.

Test 3

A third test is to mimic a worst case situation where the user is fully suspended during an emergency stop, by pulling the weight forward with the maximum allowable forward velocity of the weight support system, and releasing the dummy directly after reaching a maximum forward translation, causing

the weight to freely swing inside the weight support system. This test shall be executed with the emergency stop enabled and both without and (if possible) with the implemented gait following function (or other movement function) enabled.

Test 4

A fourth test is to mimic a worst case situation where the user is fully suspended and behavior during either a fast turn or a serious sideways motion of the user. In this case the dummy is pulled sideways and released directly after reaching the maximal sideways translation, causing the dummy to swing freely. This test shall be executed with the emergency stop enabled and both without and (if possible) with the implemented gait following function (or other movement function) enabled.

Test 5 – dynamic test

The fifth test consists of a "real world" test, only to be executed when the previous tests were passed. During this test the weight is fully supported by the weight support system. The weight support system is placed on the target floor surface, with sufficient length to reach the target speed. Via a winch the dummy will be pulled forward at the required velocity. When the weight support system reached the required velocity an emergency stop will be initiated. The dynamic stability of the weight support system will be measured.

4.2.1 Data processing

During all tests the output of the inclinometer should be recorded continuously. Data from the inclinometer may be filtered using a low pass filter with a cut-off frequency of 10 Hz.

PASS/FAIL:

The test is a PASS when the roll or pitch of the weight support system remains within 10 degrees deviation from the initial orientation of the weight support system on the target surface. The test is a FAIL when the maximum deviation for roll or pitch exceeds the max 10 degrees (e.g. when the weight support system falls over).

5 Procedure

5.1 Test Plan

The validation of the Dynamic Stability skill consists of a number of separate tests, that shall be executed in the prescribed order. Each separate test only needs to be executed when the previous test has been successfully passed.

The test should describe the system state to use during the tests and conditions for both the system and the environment during the tests, as far as these are relevant for the Dynamic stability safety skill.

5.2 Preparation

Check that the weight support system is properly configured.

Make sure the dummy can be safely used, has the proper weight and is covered in soft material to protect the weight support system during the tests.

Additional specifics for each of the separate tests will be addressed specifically in the topics below.

5.2.1 Test Arrangement

Test 1 – Lateral stability under static force

- Place the weight support system in the test location
- Attach the inclinometer to the weight support system
- Optionally:
    - Make sure the optional protective measures to prevent damage to the weight support system are setup properly
- Attach the dummy to the harness attachment points of the weight support system
- Lift the middle of the dummy to a height of 1 m
- Attach the winch used to apply a sideways movement to the dummy.
- Attach a force sensor in the connection between the winch and the dummy
- Attach the sensors to the data acquisition system
- Make sure all sensors are properly warmed up
- Take zero readings for the sensor data

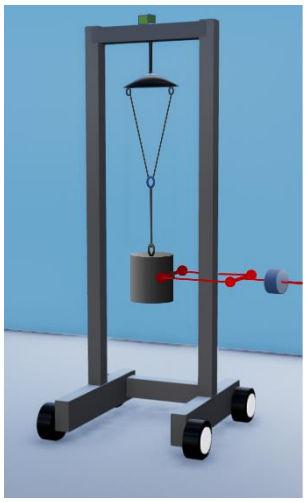

Figure 4: General structure of the test arrangement for the tests described in test 1 with the connection to the winch in red, the inclinometer in green and the force sensor in blue

Test 2 – Anterior/posterior stability under static force

- Place the weight support system in the test location
- Attach the inclinometer to the weight support system
- Optionally:
    - Make sure the optional protective measures to prevent damage to the weight support system are setup properly
- Attach the dummy to the harness attachment points of the weight support system
- Lift the middle of the dummy to a height of 1 m
- Attach the winch used to apply a forward movement to the dummy.
- Attach a force sensor in the connection between the winch and the dummy
- Attach the sensors to the data acquisition system
- Make sure all sensors are properly warmed up
- Take zero readings for the sensor data

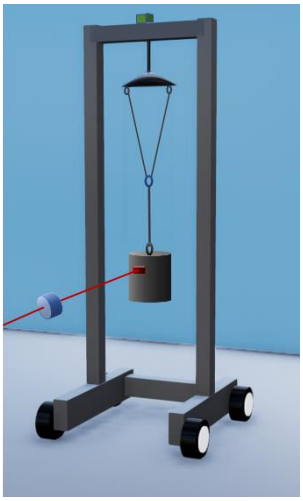

Figure 5: General structure of the test arrangement for the tests described in test 2 with the connection to the winch in red, the inclinometer in green and the force sensor in blue

Test 3 – Anterior/posterior stability after short payload translation

- Place the weight support system in the test location
- Attach the inclinometer to the weight support system
- Optionally:
    - Make sure the optional protective measures to prevent damage to the weight support system are setup properly
- Attach the dummy to the harness attachment points of the weight support system via a quick release, that can be operated from a distance.
- Lift the middle of the dummy to a height of 1 m
- Attach the winch used to apply a forward movement to the dummy.
- Attach the sensors to the data acquisition system
- Make sure all sensor(s) are properly warmed up
- Take zero readings for the sensor data

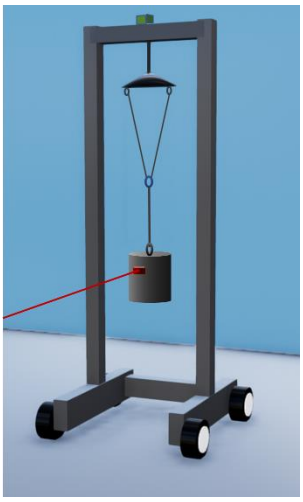

Figure 6: General structure of the test arrangement for the tests described in test 3 with the connection to the winch in red and the inclinometer in green.

Test 4 – Lateral stability after short payload translation

- Place the weight support system in the test location
- Attach the inclinometer to the weight support system
- Optionally:
    - Make sure the optional protective measures to prevent damage to the weight support system are setup properly
- Attach the dummy to the harness attachment points of the weight support system via a quick release, that can be operated from a distance
- Lift the middle of the dummy to a height of 1 m
- Attach the winch used to apply a sideways movement to the dummy.
- Attach the sensor(s) to the data acquisition system
- Make sure all sensors are properly warmed up
- Take zero readings for the sensor data

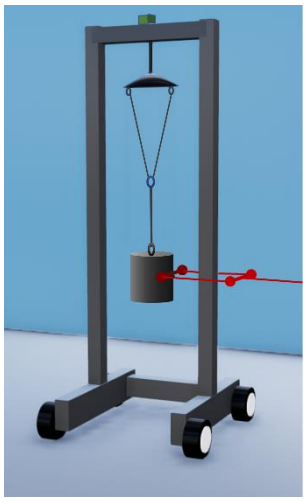

Figure 7: General structure of the test arrangement for the tests described in test 4 with the connection to the winch in red and the inclinometer in green.

Test 5 – Anterior/posterior stability after emergency stop at max velocity

- Make sure the testing area is sufficiently large
- Place the weight support system at the beginning of the area for the dynamic test
- Attach the inclinometer to the weight support system
- Optionally:
    - Make sure the optional protective measures to prevent damage to the weight support system are setup properly
- Attach the dummy to the harness attachment points of the weight support system
- Lift the middle of the dummy to a height of 1 m
- Attach the winch used to apply a forward movement to the dummy.
- Attach the sensors to the data acquisition system
- Make sure all sensors are properly warmed up
- Take zero readings for the sensor data
- Prepare the winch for a movement at the required speed, including a suitable acceleration profile.

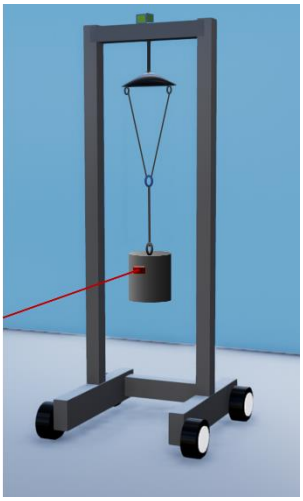

Figure 8: General structure of the test arrangement for the tests described in test 5 with the connection to the winch in red and the inclinometer in green.

5.2.2 System Conditions

When a S.F.C.* could impact the Dynamic stability skill, tests should also be executed under this S.F.C.* Describe the relevant system conditions in the test form in the Annex.

5.2.3 Environmental Conditions

Floor surface may have a significant impact on the dynamic stability skill. When the manufacturer has stated that the system can be used on specific floor surfaces, tests should be performed using these surfaces, unless a clear rationale is provided why these tests will not be relevant. Describe the relevant conditions in the test form found in the Annex.

5.3 Test Execution

Test 1 – Lateral stability under static force

- Make sure the weight support system is in normal operating mode
- Start the data acquisition system
- Use the winch to pull the dummy sideways, when possible into the support structure
- Use the winch to add within 1 second an additional force of 10% of the weight of the dummy in that lateral direction.
- Maintain this situation for 10 seconds.
- Release the additional force over 5 seconds by rolling back the winch
- Release the sideways displacement of the dummy by rolling back the winch over an interval of at least 5 seconds
- Stop the data acquisition system
- Repeat this test 3 times

Test 2 – Anterior/posterior stability under static force

Make sure the previous test was passed successfully

Subtest 2A:

- Make sure the weight support system is in normal operating mode

- Make sure the gait following function is disabled (e.g. by initiating an emergency stop)
- Start the data acquisition system
- Use the winch to pull the dummy forward 30 cm
- Maintain this situation for 10 seconds.
- Release the forward displacement of the dummy by rolling back the winch over an interval of at least 5 seconds
- Stop the data acquisition system
- Repeat this test 3 times

Subtest 2B:

- Switch on the gait following function
- Start the data acquisition system
- Use the winch to pull the dummy forward 30 cm
- Maintain this situation for 10 seconds.
- Release the forward displacement of the dummy by rolling back the winch over an interval of at least 5 seconds
- Stop the data acquisition system
- Repeat this test 3 times

Test 3 – Anterior/posterior stability after short payload translation

Make sure the previous tests were passed successfully

Subtest 3A:

- Make sure the weight support system is in normal operating mode
- Make sure the gait following function is disabled (e.g. by initiating an emergency stop)
- Start the data acquisition system
- Use the winch to pull the dummy forward 30 cm
- Release the forward displacement of the dummy via a quick release in the attachment between the winch and the dummy
- Measure the behavior of the weight support system for at least 10 seconds
- Stop the data acquisition system
- Repeat this test 3 times

Subtest 3B:

- Connect the winch to the dummy via the quick release
- Switch on the gait following function
- Start the data acquisition system
- Use the winch to pull the dummy forward 30 cm
- Release the forward displacement of the dummy via a quick release in the attachment between the winch and the dummy
- Measure the behavior of the weight support system for at least 10 seconds
- Stop the data acquisition system
- Repeat this test 3 times

Test 4 – Lateral stability after short payload translation

Make sure the previous tests were passed successfully

Subtest 4A:

- Make sure the weight support system is in normal operating mode
- Make sure the gait following function is disabled (e.g. by initiating an emergency stop)
- Start the data acquisition system
- Use the winch to pull the dummy sideways 30 cm
- Release the forward displacement of the dummy via a quick release in the attachment between the winch and the dummy
- Measure the behavior of the weight support system for at least 10 seconds
- Stop the data acquisition system
- Repeat this test 3 times

Subtest 4B:

- Connect the winch to the dummy via the quick release
- Switch on the gait following function
- Start the data acquisition system
- Use the winch to pull the dummy sideways 30 cm
- Release the forward displacement of the dummy via a quick release in the attachment between the winch and the dummy
- Measure the behavior of the weight support system for at least 10 seconds
- Stop the data acquisition system
- Repeat this test 3 times

Test 5 – Anterior/posterior stability after emergency stop at max velocity

Make sure the previous tests were passed successfully

- Make sure the weight support system is in normal operating mode
- Attach the winch to the dummy via a quick release that can be operated from a distance
- Start the data acquisition system
- Use the winch to accelerate the dummy and weight support system up to the target velocity
- When the velocity is reached, simultaneously:
  - Release the forward displacement of the dummy via a quick release in the attachment between the winch and the dummy
  - Initiate an emergency stop
- Measure the behavior of the weight support system for at least 10 seconds after initiating the emergency stop
- Stop the data acquisition system
- Repeat this test 3 times

5.4 Data Analysis

Sensor data from the inclinometer can be low pass filtered with a 10Hz cut off frequency.

Note in the report the absolute value of the maximum inclinometer value for both roll and tilt for each separate test.

Note in the report if the weight support system falls over. If so, the test is a fail.

Any of the tests counts as a FAIL if:

- Whether the system restored the upright position automatically (i.e. the system fell over during the test)
- The data of the inclinometer at any point during the test showed a tilt or roll of more than 10 degrees (or a different value if so specified by the manufacturer)

A test can be considered a PASS if the data of the inclinometer at all times remains with the 10 degree range (or a different value if so specified by the manufacturer) and when the system didn't fall over.

When all separate tests and subtests of this protocol are passed successfully, the result is a PASS, otherwise a FAIL.

5.5 Report

Make sure to report the characteristics of the RACA robot* under test as well as the specifics of the equipment used during the tests using the test form from Annex A.

Report hare as well the specific conditions under which the tests were performed.

Report the results of the tests and subtests listed in this protocol in the test form in Annex A. If any of the tests or sub-tests fails, the results of this test should be reported via the test form. The remaining tests can be skipped and the summary section of the test form can be filled in directly.

6 Bibliography

EN-IEC 60601-1:2006 Medical electrical equipment – Part 1: General requirements for basic safety and essential performance

EN-IEC 80601-2-78:2020 Medical electrical equipment — Part 2-78: Particular requirements for basic safety and essential performance of medical robots for rehabilitation, assessment, compensation or alleviation

Annex A - Test form

Test setup

System

RACA robot* - Weight support system (with gait following function)			
Manufacturer			
Model			
Serial number			
Control Software Version			
Payload			
Description	<Dummy >		
Mass [kg]	<150 kg (or other, when another maximum allowed payload is specified by the manufacturer)>		
Picture of the payload	…insert picture…		
Entire system			
Picture of the complete robot system	…insert picture…		
Allowable payload (kg)		Max weight support (%)	
Max allowed tilt (deg)		Max allowed Roll (deg)	
Safety factor used ($SF \geq 1$)			
Miscellaneous			

Sensor system

Feature	**Inclination sensor**
Manufacturer and type	
Serial Number	
Number of axis	
Calibrated range	
Accuracy	
Sampling rate	
Miscellaneous	

1D Force sensor	
Manufacturer and type	
Serial Number	
Calibrated range	
Accuracy	
Sampling rate	
Miscellaneous	

Winch	
Manufacturer and type	
Serial Number	
Miscellaneous	

Dummy	
Manufacturer and type	
Serial Number	
Mass (kg)	
Miscellaneous	

Conditions

Floor surface	*Even / Uneven*	Floor inclination (deg)	
S.F.C.*			
Miscellaneous			

Test 1 - Lateral stability under static force

Width of weight support system (cm)				
Max additional lateral force [N]				
Test ID	**Abs max tilt deviation (deg)**	**Abs max roll deviation (deg)**	**Auto recovery**	**PASS/FAIL**
#1.1				
#1.2				
#1.3				

Test 2 – Anterior/posterior stability under static force

Gait following function		Disabled		
Test ID	**Abs max tilt deviation (deg)**	**Abs max roll deviation (deg)**	**Auto recovery**	**PASS/FAIL**
#2A.1				
#2A.2				
#2A.3				

Gait following function		Enabled		
Test ID	**Abs max tilt deviation (deg)**	**Abs max roll deviation (deg)**	**Auto recovery**	**PASS/FAIL**
#2B.1				
#2B.2				
#2B.3				

Test 3 – Anterior/posterior stability after short payload translation

Gait following function		Disabled		
Test ID	**Abs max tilt deviation (deg)**	**Abs max roll deviation (deg)**	**Auto recovery**	**PASS/FAIL**
#3A.1				
#3A.2				
#3A.3				

Gait following function		Enabled		
Test ID	**Abs max tilt deviation (deg)**	**Abs max roll deviation (deg)**	**Auto recovery**	**PASS/FAIL**
#3B.1				
#3B.2				
#3B.3				

Test 4 – Lateral stability after short payload translation

Gait following function		Disabled		
Test ID	**Abs max tilt deviation (deg)**	**Abs max roll deviation (deg)**	**Auto recovery**	**PASS/FAIL**
#4A.1				
#4A.2				
#4A.3				

Gait following function		Enabled		
Test ID	**Abs max tilt deviation (deg)**	**Abs max roll deviation (deg)**	**Auto recovery**	**PASS/FAIL**
#4B.1				
#4B.2				
#4B.3				

Test 5 – Anterior/posterior stability after emergency stop at max velocity

Gait following function		Enabled		
Velocity during test (m/s)				
Test ID	**Abs max tilt deviation (deg)**	**Abs max roll deviation (deg)**	**Auto recovery**	**PASS/FAIL**
#5.1				
#5.2				
#5.3				

Summary

Date of testing	
Name of tester	
Overall conclusion	
Signature	