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Testing the Limit Range of Motion Safety Function of Upper Limb Rehabilitation Robots with an Anthropometrically Adjustable and Sensorized Dummy Limb*

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***Abstract*—Arm type or exoskeleton type rehabilitation robots move the patient's upper limb through one or more, either free or restrained connection points. The rehabilitation robot is unsafe if it moves the patient's upper limb beyond the limits of the anatomical joint ranges. A validation toolkit was developed to assess the risks of "limit anatomical joint range of movement" and "limit anatomical joint overreaching" during the regular operation of a rehabilitation robot. The validation toolkit includes an anthropometrically adjustable and sensorised dummy limb attached to the RACA (rehabilitation, assessment, compensation, or alleviation) rehabilitation robot; and a software tool for off-line risk assessment and reporting.**

I. Introduction

In manual upper and lower limb physiotherapy, the therapist is responsible for monitoring and controlling the patient's physiological parameters. The physiotherapist takes care of not exceeding the anatomical joint range limits and not attaining the pre-defined undesired anatomical joint postures. In addition, the physical rehabilitation therapy of the human locomotion system must be adapted to each patient's individual needs.

The safety of robots interacting with humans by kinetic energy exchange has become a field of interest in research for two decades. Conformance testing of upper limb rehabilitation robots, including instrumental laboratory assessments has remained unpublished except for sporadic reports [1],[2]. The landscape was changed in the 2010ies when the collaborative robots gained growing role in the industrial, the field, the medical and the domotic applications. At the end of the decade, in 2019 the basic safety and essential performance requirement standard for rehabilitation robots was published [3]. A Rehabilitation, Assessment, Compensation, or Alleviation (RACA) rehabilitation robot must monitor and control the patient's key therapeutic physiological parameters.

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While the standard constitutes the reference for developers and users, there are gaps in best practices and know-how on the safety test methodology [4]. Safety validation protocols including test devices and assessment methods help rehabilitation robot manufacturers to adopt concise testing procedures. In particular, a RACA rehabilitation robot must monitor the movement of the anatomical joints varied from patient to patient. The specific hazards in our research are related to the kinematics of the patient's actuated single anatomical joints and linkages comprising of body parts and anatomical joints. The first hazard defined is that the RACA rehabilitation robot moves any actuated anatomical joint over the pre-set lower and upper angle thresholds. The second hazard defined is that the RACA rehabilitation robot brings the whole upper limb to an overreaching posture. The motivation of the research presented in this paper was to develop a protocol including an anthropometrically adjustable and sensorised dummy limb and a software tool to off-line risk assessing and reporting the rehabilitation robot's safety function "limit patient's anatomical joint range of movement" and the "limit patient's anatomical joint overreaching".

II. Concept and Objectives

A. Upper limb kinematics related hazards

The upper limb in the biomechanics literature is modelled mostly with a 7 DOF serial mechanism, where the shoulder joint is a spherical joint with three degrees of freedom, the elbow joint is a modified hinge with one degree of freedom, and the wrist joint is a spherical joint with three degrees of freedom [5]. The shoulder complex performs five degrees of freedom motion, but the anatomical motions of shoulder elevation-depression and shoulder protraction-retraction are not considered in this research. The rigid bodies in the upper limb biomechanical model are the upper arm, the lower arm, and the hand. The anatomical joint ranges of motion (ROMs) are established based on measurements done on healthy people. Therefore, anatomical joint ROMs vary slightly from one establishing organisation to another. The most prominent normative reference values are available in the NASA, Man-system integration standards (NASA-STD-3000), N.J.S. Centre, Editor. 1987: Houston, Texas, USA [6], the Department of social & health services, Range of Joint Motion Evaluation Chart, Washington, USA [7], the American Academy of Orthopaedic Surgeons (AAOS) [8], the American medical association (AMA) [9].

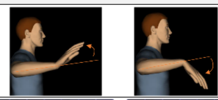
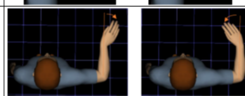
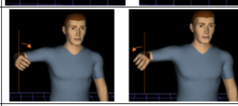
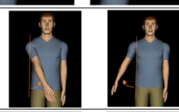
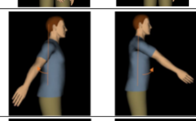
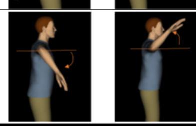
Joint	Motion type	Illustration	Range of Motion	Prohibited Zone upper limit start angle [degree]	Take Care Zone upper limit start angle [degree]	Riskless Zone [degree] from - to		Take Care Zone lower limit start angle [degree]	Prohibited Zone lower limit start angle [degree]	Percentage of take care zone
Wrist	Extension & Flexion		150	70	62,5	62,5	-72,5	-72,5	-80	5%
	Radial & Ulnar Deviation		50	20	17,5	17,5	-27,5	-27,5	-30	5%
	Pronation & Supination		160	80	72	72	-72	-72	-80	5%
Elbow	Flexion & Extension		150	150	142,5	142,5	7,5	7,5	0	5%
Shoulder	Adduction & Abduction		210	180	169,5	169,5	-19,5	-19,5	-30	5%
	Flexion & Extension		240	180	168	168	-48	-48	-60	5%
	External & Internal rotation		160	90	82	82	-62	-62	-70	5%

Figure 1. Definition of the upper limb anatomical joint motions, their Ranges of Motion, the upper and lower limit angles, and the risk zones for anatomical joint limit risk

# Overreaching Risk	Only if the three anatomical joint angles are simultaneously in these ranges!	Take care zone range [degree]		Prohibited angle [degree]
wrist	Extension & Flexion	7.5	-7.5	0
	Radial & Ulnar Deviation	2.5	-2.5	0
elbow	Extension & Flexion	7.5	-7.5	0

Figure 2. Definition of risk zones for anatomical joint overreaching limit risk

The upper limb anatomical joint motions, their Ranges of Motion, the upper and lower limit angles have been defined according to Kapandji [10] and AAOS) [8]). Upper limb hazardous situations could occur and lead to, e.g. a joint dislocation when the movement of the joint goes beyond the anatomical joint ROM limits [11]. An anatomical joint ROM limit hazard is a general term used when a particular anatomical joint reaches or exceeds the upper or lower thresholds of its ROM. The anatomical joints can experience seven different anatomical joint limit hazards, e.g., Wrist Extension & Flexion limit hazard, and so on within the selected kinematical model of the upper limb. The second hazard related to upper limb kinematics, the overreaching posture, is referred to when a person attempts to reach a position outside the upper limb's workspace to perform a task. In our approach, anatomical joint overreaching hazard occurs when there is no relative angle between any neighboring body parts in the upper limb. Therefore, when the upper arm aligns fully with the lower arm, and the lower arm aligns fully with the hand, the upper limb is anatomically overreaching.

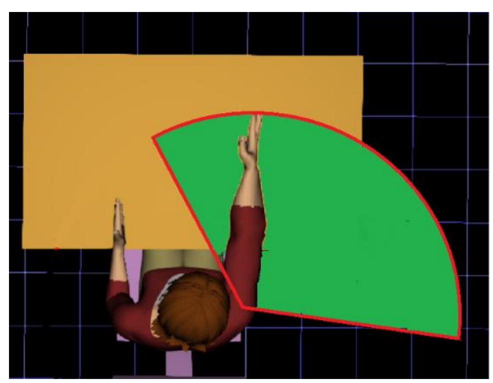


Figure 3. Illustration of the right-hand anatomical joint overreaching hazard

Expressed in joint angles the hazard is present when the elbow flexion-extension angle is 0°, the wrist flexion-extension angle is 0°, and the ulnar-radial deviation angle is 0°. Due to the nature of the upper limb kinematics, the anatomical joint overreaching risk may occur only at the outside perimeter of the upper limb's workspace (Figure 3.).

B. *Definition of the risk zones*

For anatomical joint limit risk analysis, the tester needs first to specify the anatomical joint limit values for each joint ROMs (Figure 1.). The upper and the lower limit start angles vary among patients according to their disease, therapeutic progress status, age, and other personal characteristics. The tester then needs to define the percentage of the Take Care zone over the anatomical joint ROMs in the last column. This way, three separate risk zones are defined for each anatomical joint movement ROM: the Red zone is the Prohibited zone, the Orange zone is the Take Care zone, and the Green zone is the Riskless zone. The Prohibited zone is when the anatomical joint is experiencing a hazardous posture that cannot be allowed during manual or robot-assisted therapy. The Take Care zone is when the anatomical joint moves near a hazardous posture determined by the previously defined percentage factor. The Riskless zone refers to safe movement without any danger.

For anatomical joint overreaching risk analysis, the tester needs to enter the individual upper limit and lower limit start angles into the risk zone table (Figure 2.) to define the thresholds of the Take Care zone. This way, three separate risk zones for the anatomical joint overreaching risk are defined: the Red zone is the Prohibited zone, and the Orange zone is the Take Care zone. Upper limb postures represented different angles than those of the Prohibited zone or the Take Care zone are considered riskless in terms of the anatomical joint overreaching risk.

III. DEVELOPMENT OF THE DUMMY LIMB TESTING DEVICE

For testing the RACA upper limb rehabilitation robot an artificial dummy upper limb equipped with seven rotational angle encoders in the shoulder, elbow, wrist joints, and a supporting stand has been developed. The dummy upper limb (Figure 4) meets the following requirements:

- testing in sitting posture (with alteration of the stand, a lying posture setup is also feasible),
- mounting places on the stand for the left arm and right arm therapy,
- shoulder's height adjustability in the range between 5%ile female and 95%ile male anthropometrical sizes,
- upper and lower arms' lengths adjustability in the range between 5%ile female and 95%ile male anthropometrical sizes,
- emulating the seven anatomical joint motions of the human upper limb (Figure 1.)
- rotational angle sensor built-in in each anatomical joint.
- solid cosmetic hand.

The shell components of the dummy upper limb are 2D printed. The joint structures include rolling bearings (e.g. No.31 and No.32 in Figure 5.), pressed into inner and outer aluminum bushings (e.g. No.4, No.5, No.17, and No.18). All cables are routed internally to the rotary sensors, to (e.g. No.26), the signal processing microcontroller unit, and to the external data acquisition device (Figure 4.).

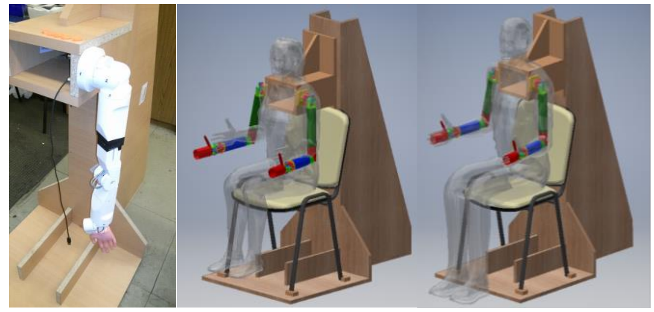


Figure 4. The dummy limb's (left) side, size and shoulder height are adjustable in the range from 5%ile female (midle) and 95%ile male (right) anthropometric data

Spring pre-loaded latches (e.g. No.15) help the tester set the length of the lower and upper arms of the dummy limb. Push buttons (e.g. No.27) serve the easy change of the dummy limb to left or right side configurations. Brake plugs (e.g. No.23) are available for safe transportation and accurate zero offset calibration. The signal processing microcontroller unit collects the data of the rotational joint encoder sensors using a Daisy-Chain SPI communication protocol. A Python PC program reads the measured data via a USB port with 10-bit resolution and configurable rate from 1 Hz to 5000 Hz. The PC program then logs the data into a Comma-Separated Values (CSV) file format.

IV. TEST PROCEDURE

The dummy limb based testing system is suitable for testing all the relevant passive and active upper limb RACA rehabilitation robot operations. The test reports should determine the outcome metrics as follows:

- Does any and if so, which of the shoulder, elbow, and wrist anatomical joints move in the Prohibited and in the Take Care anatomical joint ROM zones? (Yes/No, list of anatomical joint motion type, time of occurrence)

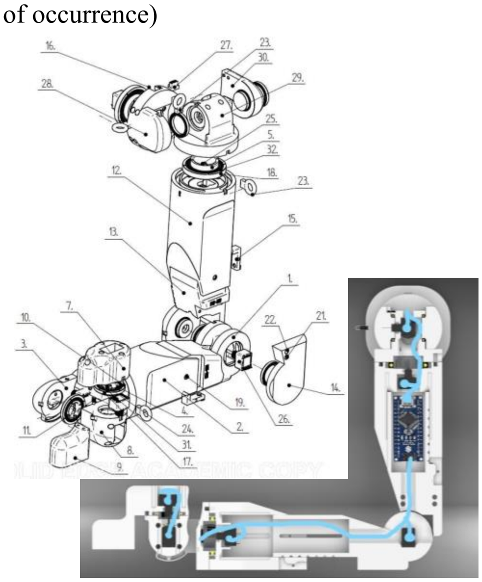


Figure 5. Exploded 3D assembly drawing of the dummy upper limb (left-up); cross-sectional view of the dummy upper limb with the sensor data processing microcontroller board (right-bottom)

- The rate of anatomical joints movement duration in the Prohibited and in the Take care zone over the entire therapeutic movement duration. (%)
- Does the upper limb move in the Prohibited and in the Take Care Anatomical Joint Overreaching posture zones? (Yes/No, list of anatomical joint motion type, time of occurrence)
- The rate of the Prohibited and the Take care zone Anatomical Joint Overreaching movement duration over the entire therapeutic movement duration. (%)

Figure 6. shows the test plan that is valid for all test conditions. The tester may opt for visual verification of the risk postures in an ergonomics analysis and simulation software tools equipped with Mocap (Motion Capture) data interface. The navigation functions of such ergonomics analysis and simulation tools allow the tester to jump and visually cross-check each frame marked with a risk. In the described case, a data interface has been developed for the SIEMENS Tecnomatix Jack™ 8.4 software tool.

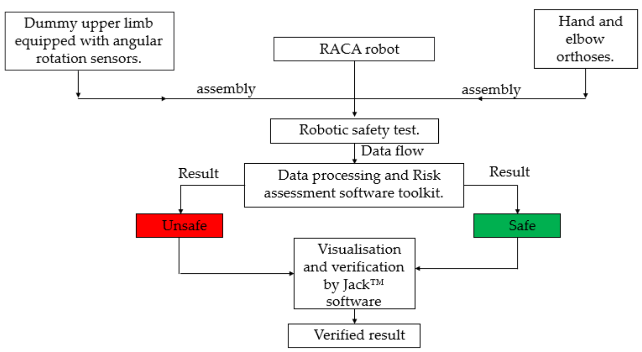


Figure 6. Flow chart of test for assessing the “limit anatomical joint range of movement” and “limit anatomical joint overreaching" risks

V. TEST REPORTS

The Data processing and Risk assessment software toolkit (downloadable from http://www.oori.bme.hu/dorothy/robotic_measurements_1-5_and_data_analysis_sheet.zip) helps the tester to identify the hazard postures during a robotic rehabilitation session. The first sheet (Figure 8.) includes under the light blue headers the raw measurement data logged by the rotary encoders of the dummy limb. To visually verify the risk postures in an ergonomics analysis

Figure 7. Safety assessment of a RACA rehabilitation robot. Left: the physiotherapist programs the RACA rehabilitation robot by hand guiding the dummy upper limb; Right: the RACA rehabilitation robot autonomously exercises the dummy upper limb.

and simulation tool equipped with Mocap (Motion Capture) data interface, the raw measurement data are extended with time stamps, transferred from encoder to anatomic ranges, and transformed into a Mocap readable format and auto-filled under the green headers (Figure 8.). The numerical and graphical format safety test reports can be seen on the third sheet.

If anatomical joint ROM or anatomical joint overreaching risks are calculated, the software colurs the corresponding cell into orange or red (Figure 9.) The Data processing and Risk assessment software toolkit can generate numerical and a graphical test reports. The graphical format test report includes eight pie charts that summarize the safety test results (Figure 10.). The RACA rehabilitation robot has passed the test if no red colour is present on any pie chart. The size of the red and the oranges pies refer to the rate of the time elapsed in the Prohibited and the Take care zones respectively. The numerical format test report gives the total time frames and the sampling frequency for that particular test in the first row (Figure 11.). In rows 3-9, it reports the total number of frames in which the anatomical joint postures

frame [-]	time [s]	shoulder ext\flex [deg]	shoulder abd\add [deg]	shoulder in_rot\ext_rot [deg]	elbow ext\flex [deg]	wrist sup\pro [deg]	wrist rad_dev\uln_dev [deg]	wrist flex\ext [deg]	shoulder ext\flex [deg]	shoulder abd\add [deg]	shoulder in_rot\ext_rot [deg]	elbow ext\flex [deg]	wrist sup\pro [deg]	wrist rad_dev\uln_dev [deg]	wrist flex\ext [deg]	time frame	wrist frame	elbow frame	shoulder frame
0	0.000	0.0	4.6	-7.0	84.4	83.3	-0.4	-12.0	0.0	4.6	-7.0	84.4	83.3	-0.4	-12.0	frame[0]=0;	frame[0]= (-0.006136,-0.208621,1.454214);	frame[0]= (1.472622);	frame[0]= (-0.122718,0.079767,0);
1	0.033	0.0	4.9	-7.0	84.4	83.3	-0.4	-11.6	0.0	4.9	-7.0	84.4	83.3	-0.4	-11.6	frame[1]=0.0333;	frame[1]= (-0.006136,-0.202485,1.454214);	frame[1]= (1.472622);	frame[1]= (-0.122718,0.085903,0);
2	0.067	0.0	4.6	-7.0	84.7	83.3	0.0	-11.6	0.0	4.6	-7.0	84.7	83.3	0.0	-11.6	frame[2]=0.0667;	frame[2]= (0,-0.202485,1.454214);	frame[2]= (1.478757);	frame[2]= (-0.122718,0.079767,0);
3	0.100	0.0	4.6	-7.0	84.4	83.3	-0.4	-12.0	0.0	4.6	-7.0	84.4	83.3	-0.4	-12.0	frame[3]=0.1;	frame[3]= (-0.006136,-0.208621,1.454214);	frame[3]= (1.472622);	frame[3]= (-0.122718,0.079767,0);
4	0.133	0.0	4.6	-7.0	84.4	83.3	-0.4	-11.6	0.0	4.6	-7.0	84.4	83.3	-0.4	-11.6	frame[4]=0.1333;	frame[4]= (-0.006136,-0.202485,1.454214);	frame[4]= (1.472622);	frame[4]= (-0.122718,0.079767,0);
5	0.167	0.0	4.6	-7.0	84.7	83.3	-0.4	-12.0	0.0	4.6	-7.0	84.7	83.3	-0.4	-12.0	frame[5]=0.1667;	frame[5]= (-0.006136,-0.208621,1.454214);	frame[5]= (1.478757);	frame[5]= (-0.122718,0.079767,0);

Figure 8. Raw measurement data under blue header and pre-processed data under green header in the Data processing and Risk assessment software toolkit

Time	Wrist Extension\Flexion	Wrist Radial\Ulnar Deviation	Wrist Pronation\Supination	Elbow Flexion\Extension	Shoulder Adduction\Abduction	Shoulder Flexion\Extension	Shoulder Exernal\Internal Rotation	Overeaching detection
[illegible]	-11.60	-26.02	88.24	84.73	4.92	0.00	-7.38	Not overreaching
57.433	-11.60	-26.72	88.24	84.38	4.92	0.00	-7.03	Not overreaching
57.467	-11.60	-27.07	88.24	84.73	4.92	0.00	-7.38	Not overreaching
57.500	-11.60	-27.77	88.24	84.73	4.92	0.00	-7.38	Not overreaching
57.533	-11.60	-28.13	88.24	84.73	4.92	0.00	-7.03	Not overreaching
57.567	-11.25	-28.48	88.24	84.38	4.92	0.00	-7.38	Not overreaching
57.600	-11.25	-28.83	88.24	84.73	4.92	0.00	-7.38	Not overreaching
57.633	-10.90	-29.53	88.24	84.38	4.92	0.00	-7.38	Not overreaching
57.667	-11.25	-29.88	88.24	84.38	4.57	0.00	-7.38	Not overreaching
57.700	-11.25	-30.23	87.89	84.73	4.57	0.00	-7.38	Not overreaching
57.733	-10.90	-30.94	87.89	84.73	4.92	0.00	-7.38	Not overreaching
57.767	-10.90	-31.29	87.89	84.73	4.92	0.00	-7.38	Not overreaching

Figure 9. Risk calculation and presentation by the risk zone colour (Figure 1.)

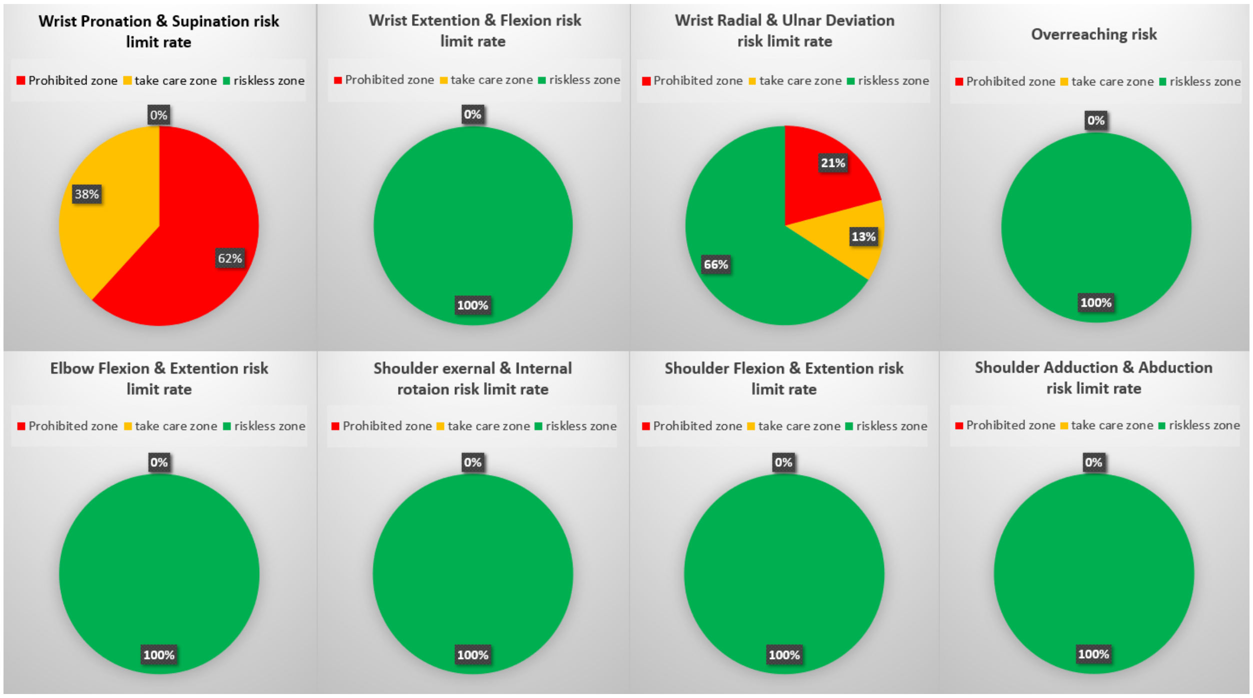


Figure 10. Graphical test form of the anatomical joint ROM risk test

fall into the Prohibited zone (red), or into the Take Care zone (orange), or the Riskless zone (no colour). In rows 11-13, it reports the total number of frames in which the anatomical joint overreaching postures fall into the Prohibited zone (red), or into the Take Care zone (orange), or the Riskless zone (no colour). The RACA rehabilitation robot has passed the test if the number of frames in which the anatomical joint postures fallen into the Prohibited zone (red) is equal to zero, and the anatomical joint overreaching postures fallen into the Prohibited zone (red) is equal to zero. A quick visual check of the pass condition is provided if no red colour is present in the report. Any non-zero frame numbers in the Prohibited zone means no-pass test for the RACA rehabilitation robot

CONCLUSIONS

The artificial dummy upper limb equipped with seven rotational angle encoders in the shoulder, elbow, wrist joints, and the Data processing and Risk assessment software toolkit were developed and validated in five real-life RACA rehabilitation robot sessions (http://www.oori.bme.hu/dorothy/DOROTHY_D2.2.pdf and http://www.oori.bme.hu/dorothy/robotic_measurements_1-5_and_data_analysis_sheet.zip). The validation reports (See the report for session 1 on Figure 11.) inform the tester whether the RACA robot under investigation has passed the safety test.

The Data processing and Risk assessment software toolkit and the dummy limb can be used with any type of upper limb rehabilitation robot. The software toolkit is flexible for a rapid integration with other instrumented dummy limbs of prosthetic arms. The use of dummy limb as testing device eliminates the biggest disadvantage of motion capture based systems: the rehabilitation robot's connections points and structural parts cover the anatomic landmark points required for the placement of optical markers.

The validation has also revealed a number of options for future development. All measurement data are at disposal to assess anatomic joint angular speed (overspeeding) risk. User friendliness of the safety assessment can be enhanced if the Data processing and Risk assessment software toolkit could enable online real-time safety assessment of a RACA rehabilitation robot. Using open-source software, a mannequin-based graphical motion visualization module could be integrated with the Data processing and Risk assessment software toolkit.

total frames	2414	freq. [Hz]	30	
Joint	Movement	Number of risk postures for joint limit risk	Number of take care postures for joint limit risk	Number of frames without joints risk
wrist	Extension & Flexion	0	1	2413
	Radial & Ulnar Deviation	503	322	1589
	Pronation & Supination	1491	923	0
elbow	Flexion & Extension	1	0	2413
shoulder	Adduction & Abduction	0	0	2414
	Flexion & Extension	0	0	2414
	Exernal & Internal rotaion	0	0	2414
Number of overreaching postures		1		
Number of overreaching take care postures		0		
Number of frames without overreaching risk		2413		

Figure 11. Numerical test form of the anatomical joint ROM risk test

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