Cross-Industry Standard Test Method Developments – from Manufacturing to Wearable Robots*

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Abstract: Manufacturing robotics are moving towards human-robot collaboration with light duty robots being used side-by-side with workers. Similarly, exoskeletons that are both passive (spring and counterbalance forces) and active (motor forces) are worn by humans and move body parts. Exoskeletons are also called wearable robots when they are actively controlled using a computer and integrated sensing. Safety standards now allow, through risk assessment, both manufacturing and wearable robots to be used. However, performance standards for both systems are still lacking. Ongoing research to develop standard test methods to assess performance of manufacturing robots and emergency response robots can inspire similar test methods for exoskeletons. This paper describes recent research on performance standards for manufacturing robots, as well as search and rescue robots. It also provides a discussion on how performance of wearable robots can benefit from using the same test methods.

Key words: wearable robot, exoskeleton, cross-industry, artifact, standards, grasping

1 Introduction

Wearable robots, such as exoskeletons, are a broad category that includes systems that guide humans to assist them in moving their bodies as well as human-guided systems that augment body motions and forces for added speed or strength. Wearable robots can be partial- or full-body systems and are currently being developed throughout many countries around the world [1]

Wearable robots have current or potential applications in rehabilitation [2], elderly care [3, 4], military operations [5], and manufacturing [6]. The International Organization of Standardization (ISO) 13482 personal care robot safety standard was developed to provide safeguards for elderly or other persons using wearable robots, such as exoskeletons, and provide some cross-industry [7] consideration to manufacturing, the military, or other industries. Although ISO 13482 has been published, it includes no normative references to directly assess risks or hazards, design, verification, installation, and validation. Additionally, [8] suggests that there are some types of exoskeletons that haven't been developed to demonstrate, for example, "significant decrease in the metabolic demands of walking or running" where some measures for the standard may be required.

Cross-industry exoskeleton technology and collaborative industrial robots require both safe human-robot performance and capabilities. However, unlike for collaborative industrial robots, there are currently no standard test methods for measuring the safety and performance of wearable robots. Non-wearable (collaborative) robots, such as industrial robots, mobile robots, and mobile manipulators, have been technologically improving, many of which allow robots and humans to work side-by-side or robots to work with other robots [9]. Collaborative robot safety standards have been developed and continue to evolve. [Ref: R15.06-2012, ISO 10218 and TS 15066]

Safety and performance test methods are being developed so that manufacturers and users can evaluate and compare capabilities of emergency response robots [10] and industrial robots against the requirements of their applications and particular tasks. Test methods for these industries can provide valuable insights for the subject wearable robot standards, including what metrics should be considered, what safety and/or performance test methods should be developed, and how generic test methods demonstrate a measure of safety and/or performance.

This paper will begin by identifying the types of wearable robots used in the manufacturing industry that require safety and performance testing and will consider metrics for testing these systems. Standard test methods that have been, or are currently being, developed for emergency response robots and for industrial collaborative robots will be discussed. This will be followed by a brief discussion on the process considered for test method development. Lessons learned and basic concepts from response and industrial robot areas will then be considered towards the development of test methods for wearable robots.

2 Types of wearables to be tested

Both passively- and actively- controlled exoskeletons can provide useful capabilities for the manufacturing industry. Passive exoskeletons, such as Fortis shown in Figure 1 (a), are not robots although they possess capabilities that extend the worker's capabilities for longer periods of time. Passive systems can be adapted to the wearer and to the task with mechanical adjustments to the system. Similarly, actively controlled exoskeletons, considered wearable robots, provide capabilities that can potentially be programmed to adapt to the

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wearer and to the task. An example of an actively-controlled exoskeleton is shown in Figure 1 (b) where a worker demonstrates his increased lifting capability at a shipyard. Actively-controlled exoskeletons use electronics, motors, computers, and intelligent software control to provide adaptability to the wearer and task.

a

b

Figure 1 – Examples of: (a) passive (courtesy of Lockheed Martin via Wired [5][*]) and (b) active exoskeletons (courtesy of Daewoo Shipbuilding and Marine Engineering via Discovery News [11]).

Recent research by Herr and others described in [6] have suggested that there can be metabolic energy cost reduction when wearing some types of "parallel-limb exoskeletons" and other shoes. This is one measure of safety and performance that can be used to define exoskeleton usefulness. However, other metrics that are not currently in the literature go beyond metabolic cost/increase. In [6], there are also some surveyed exoskeletons that can provide increased lift capacity, although there is, little supporting information available on these systems being used on a variety of people (i.e., various sizes, shapes, genders, ages, etc.).

Metrics for both passive and active exoskeletons, each considered a generic system-under-test (SUT), are similar, including:

- Duration: maximum time that a task can be performed with the SUT as compared to performing the task without the SUT
- Speed: velocities that can be achieved and sustained with the SUT as compared to performing the task without the SUT
- Pose: uncertainty - accuracy/resolution (e.g., precision to move to a commanded location) and repeatability (e.g., move to the same commanded location more than once) for the SUT to position and orient the operator's arm or leg as commanded. Positioning error of a tool or device when held by the controlled arm or leg is the measured component.
- Back-drivability or Control Force: force required to resist component reaction or move any or all

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components of the SUT when they are both driven or not driven.

- Put-on/Take-off Complexity: difficulty in putting on or removing the SUT
- Ease of use: simplicity of initial training and ease of control of the SUT as it allows or improves task completion performance
- Vertical Maneuvering: capability, speed to traverse inclines, steps, undulating terrain
- Horizontal Maneuvering: capability, speed to traverse forward, back, side-to-side

Other metrics are listed in [1] for exoskeletons being considered or used for rehabilitation, including: comfort, cost, portability, battery life, range of use, and several others related to maneuvering the body.

3 Test methods from non-wearable robots

The market for non-wearable or collaborative robots has been recently increasing, perhaps in part due to ISO 10218-2 and ISO/TS 15066 [14] approvals, as well as research activities. The United States National Institute of Standards and Technology (NIST) has been performing research on collaborative robots within its Performance of Collaborative Robot Systems Project [12] as part of the Robotics for Smart Manufacturing Program.

Robots for flexible factory environments are limited by the robots' inability to coordinate, communicate, and understand their actions, roles, and task statuses to effectively and efficiently collaborate with others. Limitations are driven by both the absence of tools and protocols needed for describing collaborative functions, and the complete lack of metrics for assessing how well robots can work together and with humans. The project is in the process of providing the methods, protocols, and metrics necessary to evaluate the collaborative capabilities of robot systems.

Similarly, emergency response robotics is being researched at NIST within the Robotics Test Facility [13], which is a laboratory for developing standard methods of measuring robot performance. The facility houses artifacts and equipment for measuring how well robots perform under a variety of tasks that abstract real-world challenges. The application domains supported by this facility include urban search and rescue, bomb-disposal, military ground operations, disaster response, and manufacturing. Artifacts are designed to be abstract representations of the environment and task challenges that a particular requirement addresses. Experiments are conducted by running a wide variety of robots through the prototype test methods to understand how to best capture data and to refine the physical artifacts and methodology.

The wearable robots community can leverage experience gained from the performance test method development and applications from both manufacturing collaborative robotics and search and rescue robotics research. The following sections describe industrial and response robots standards and test methods that may have aspects that could be considered for the development of wearable robot standards.

3.1 Industrial robot standards and test methods

Current standards and working documents forming the foundation for eventual standards for industrial robots, service robots, mobile robots, mobile manipulators, and robotic hands that may be of interest to the wearable robots community are listed here.

Standards

Industrial Robots:

- International Organization of Standards (ISO) [14] 10218 -1,2: Robots and robotic devices — Safety requirements for industrial robots – Parts 1 and 2
- ISO/Technical Specification (TS) ISO/TS 15066 Robots and robotic devices - Safety requirements for industrial robots - Collaborative operation
- Robot Industry Association (RIA) [15] 15.06-2012 - American National Standard for Industrial Robots and Robot Systems-Safety Requirements.

Service Robots:

- ISO/DIS 18646-1 Robots and robotic devices -- Performance criteria and related test methods for service robot -- Part 1: Locomotion for wheeled robots

Mobile Robots:

- American National Standards Institute/Industrial Truck Standards Development Foundation (ANSI/ITSDF) [16] B56.5-2012, Safety Standard for Driverless, Automatic Guided Industrial Vehicles and Automated Functions of Manned Industrial Vehicles
- ASTM [16] F45.02 Navigation (Performance) for Driverless Automatic Guided Industrial Vehicles (Working Document WK48955)

Mobile Manipulators:

- ASTM F45.02 Docking (Performance) for Driverless Automatic Guided Industrial Vehicles (Working Document WK50379)
- RIA 15.08: Working Group on Mobile Industrial Robots Safety

More detail is provided for some draft standard test methods that could have greater relevance to the exoskeleton community.

Navigation

Recent research on industrial robots in the area of navigation, docking, and ground truth system measurement systems provides an order of magnitude improved measurement basis for test method development [18]. Figure 2 shows an example navigation concept currently being considered for the ASTM F45.02 navigation standard.

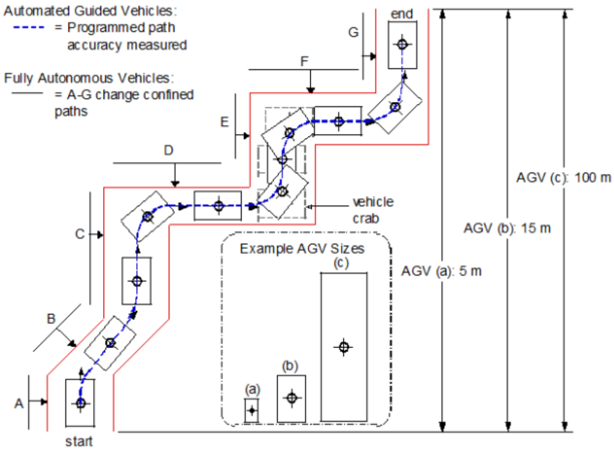


Figure 2. Example reconfigurable apparatus for navigation tests for various AGV sizes.

The moveable barriers increase the path confinement per trial. An automatic guided vehicle (AGV) or mobile robot is to traverse the reconfigurable path without contacting the barriers. The vehicle performance is measured by how well it follows the path without detecting the barriers as their width decreases.

<u>Docking</u>

Positioning, or "docking", of the vehicle and onboard equipment after navigating allows the vehicle to access a pallet, tray-station, or a table of parts for assembly. Measurements of how well the vehicle docking performs is therefore critical for users to understand vehicle integration for assembly, material handling, etc. Docking is also being studied using collaborative robots and artifacts through use of a mobile manipulator which includes a robot arm onboard an AGV. Figure 3 shows the evaluation of mobile manipulator performance using a reconfigurable mobile manipulator artifact (RMMA).

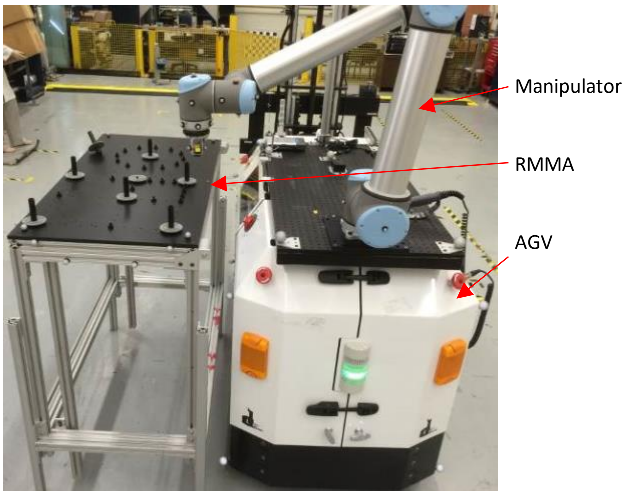


Figure 3. Docking performance measurement of a mobile manipulator with a reconfigurable mobile manipulator artifact (RMMA). Small spheres mounted on both the mobile manipulator and RMMA are used as fiducials for an optical ground truth system to measure mobile manipulator motion relative to the RMMA during test method development.

The RMMA can be reconfigured to be horizontal as shown in the figure or vertical, as well as positioned below or above the mobile manipulator. The RMMA allows for a non-contacting manipulator pose to align a laser retroreflector with reflector fiducials on the artifact to within a few millimeters, dependent upon required uncertainty measurement. Static base, indexed base (i.e., stop and measure the RMMA followed by moving to a new position, stopping and measuring at the second position), and dynamic base positioning can be tested using the RMMA.

Another test used in evaluating performance of AGVs, mobile robots, and mobile manipulators is obstacle detection and avoidance. Reference [18] also describes this test method.

<u>Grasping</u>

Current industrial grippers are typically two-fingered, pinch-type. Three or more-fingered, industrial grippers are being developed for more dexterous manufacturing applications, such as assembly [19]. Some advanced grippers resemble human hands, although most don't have five digits. Figure 4 shows an example of an advanced, highly dexterous robotic hand being developed and example prehension of typical objects [20] [21].

Grasping is another area in which performance test methods can be considered. A proposed roadmap for dexterous manipulation [22] includes impact areas focused on several aspects of dexterous arm and hand performance, including sensing, motion, control, and applications.

Test methods are expected to address at least some level of the following capabilities:

- Hand Mechanics
    - Position control
    - Torque control of fingers/digits
    - Grasp capacity (e.g., graspable object size and mass)
    - Grasp types supported
    - Accuracy
    - Repeatability

Figure 4. Example advanced highly dexterous robotic hand being developed [21]

- Tactile Sensing:
    - Normal forces and pressure
    - Force and impact sensitivity
    - Location of touch
- Functional Tasks
    - Quasi-static and dynamic effects on grasp stability
    - In-hand manipulation of objects
    - Touch sensitivity (e.g., using touch to control finger position/force)

Draft test methods are being developed for robotic hands and advanced grippers under a metrics working group for an Institute of Electrical and Electronic Engineers Technical Committee on Robotic Hand Grasping and Manipulation. [23] [24]

Hand exoskeletons that can benefit from industrial gripper test methods are being embedded in an astronaut's glove [25] and as hand exercise devices [26].

The aforementioned roadmap [22] also includes dexterous robot arms, proposing less complex performance metrics than for dexterous grippers, such as:

- Reachable volume (i.e., the positions and orientations that an *arm* can achieve within the workspace)
- Operational space (i.e., the positions and orientations in which the arm and/or hand can effectively perform the required operation.
- Confined space access
- Grasping objects while in motion

3.2 Response robot test methods

Several performance standards have been created through the ASTM International standards development organization under the E54 Committee for Homeland Security Applications. [17]

Specifically, the E54.08 Subcommittee-developed Standard Test Method Suite for Evaluating Emergency Response Robot Capabilities focuses on measuring capabilities of robots with respect to mobility, energy/power, radio communication, durability, logistics, safety, human-system interaction (HSI), sensors, and autonomy, although most response robots are teleoperated. This suite of standards can provide cross-industry test methods that may apply to wearable robots and passive systems. Below are the potentially relevant standards (noted by "ASTM"), working documents under development (i.e., indicated by 'WK' prior to a number), and planned standards for future development:

Mobility, Confined Area Terrains and Obstacles:
- Gaps (ASTM E2801),
- Hurdles (ASTM E2802),
- Inclined Planes (ASTM E2803),
- Stair/Landings (ASTM E2804),
- Gravel (WK35213),
- Sand (WK35214)
- Continuous Pitch/Roll Ramps (ASTM E2826)
- Crossing Pitch/Roll Ramps (ASTM E2827)
- Symmetric Stepfields (ASTM E2828),

Human-Systems Interaction:
- Maneuvering, Sustained Speed (ASTM E2829)†
- Maneuvering Tasks, Towing Grasped/Hitched Sleds (ASTM E2830)
- Maneuvering Tasks, Post/Hole Slaloms
- Search Tasks, Random Mazes with Complex Terrain (ASTM E2853),
- Navigation Tasks: Hallway Labyrinths with Complex Terrain (WK33260)
- Confined Space Voids with Complex Terrain (WK34434)

Sensors:
- Image Acuity (WK42363)
- Ranging: Spatial Resolution (planned)
- Localization and Mapping: Hallway Labyrinths with Complex Terrain, (planned)
- Localization and Mapping: Wall Mazes with Complex Terrain, Sparse Feature Environments (planned)

† Maneuvering Tasks are under the Human-System Interaction category because they are performed at a standoff distance by the operator, requiring high levels of situational awareness to perform successfully.

Manipulation:

- Door Opening and Traversal Tasks (WK27852)
- Heavy Lifting: Surrounding Area (WK44323)
- Dexterous Inspection (planned)
- Dexterous Retrieval (planned)

Examples of some of the above standard performance test method artifacts are shown in Figures 5 [13].

Current response robot test methods have been, or are being, developed to make it simple to measure, for example, how well a robot navigates around an obstacle on a level floor. Incrementally more challenging conditions can also be tested, for example to measure how well a robot navigates inclined planes, steps, undulating floors or complex terrains, and around obstacles as illustrated in Figure 5. Additionally, the navigation and obstacle avoidance tests can be combined with vision tests since most response robots are teleoperated. This combination also provides a human-in-the-loop test where a robot's pitch and roll can skew the operator's reference frame for the images provided by the onboard camera(s),

a

b

c

d

Figure 5. Examples of (a) inclined planes, (b) stairs, and (c) varying terrain test apparatus and actual varying terrain (above the apparatus). (d) Example artifacts of increasingly complex terrains.

thus can hinder robot control. Each test generically simulates a particular capability which response robots must possess to be useful in critical situations. For example, undulating floors or complex terrains may appear in collapsed buildings where search and rescue robot missions are required.

4 Test Method Development

Industrial robot and search and rescue robot test methods have been, or are being, developed in a similar manner. In the case of ASTM F45 performance standards development, the mobile robot and AGV industries were surveyed to establish their current and potential system capabilities to meet specific user application requirements.

In the case of ASTM E54.08.01 response robot standards development, the process began with in-depth workshops with emergency responders to identify key performance metrics and deployment scenarios, particularly focusing on urban search and rescue operations. Over 100 requirements were initially identified over the course of three workshops and were used to guide the test method development process. [27] Over time, additional requirements are added from new constituencies, such as bomb squads (e.g., for counter-vehicle-borne improvised explosive devices).

Test method development begins with establishing metrics and as with any experiment, isolation of variables and hypothesized results follow. Test methods that allow simple, isolated measurements of capabilities, for example navigation, can be then broken down into simple-through-complex tests. For example, open-area navigation of a straight line, followed by the addition of a curve, and then added obstacles in the path, and lastly, increasingly narrower path confinement is one simple test method. In the response robots test suite, the configuration of a robot under test is to remain unchanged through all the test methods. In other words, if a heavier battery is used to extend the robot's endurance in the power/energy tests, it must be in place during mobility tests, such as stair climbing or inclines, where a changed center of gravity may impact the performance. This provides realistic information about configuration tradeoffs.

Ideally, the method does not require expensive, resource-intensive measurement systems and procedures, and thus minimalist test method apparatus design and use must be considered. Apparatus materials should resemble the actual robot application environment and be readily available, relatively inexpensive, and simple to construct as in the apparatuses shown in Figures 2 and 5 for industrial and response robot test methods, respectively. Alternatively, the need for high precision measurement may require a different approach. The RMMA shown in Figure 3 was designed and machined to be relatively precise as compared to positioning capability of a mobile manipulator. Even in this case, it is expected that the components can be fabricated through additive manufacturing (three-dimensional printing) to save cost and avoid machining while still maintaining required precision.

The test method administration, procedures, and reporting methods are established. Periodic reviews of draft test methods with potential end users and robot developers, resulting in iterative improvement of the test method design and procedures are also desirable for ensuring that the resulting standards are useful and usable.

5 Cross-Industry test methods

This section discusses how industrial and response robot navigation, docking, combined navigation and docking, and grasping test methods could be applied to wearable robots. Methods developed for industrial and response robot performance tests can help minimize the development process or guide designs for wearable robots. For example, one type of navigation surface may be applicable to one manufacturer's exoskeleton and may not be applicable to another. Increasing complex terrain navigation may also show limitations throughout the robot development process. Similarly, exoskeleton motor, spring, and/or counterbalance may be tuned for lifting or manipulating heavy loads and may not be tuned for threading a needle. More specific applications of previously discussed concepts follow.

Navigation

Wearable robots for lower body movement can perform tests similar to manufacturing mobile robots and AGVs demonstrating navigation through confined areas. For example, barriers or a series of objects can be placed along a path that the human must follow while wearing the robot. The walls can be moved closer to the path and if the human collides with the barriers or objects, the metrics of stability, maneuverability, and velocity can be measured. An additional test could be to test avoidance or maneuverability when obstacles suddenly appear in the human's path.

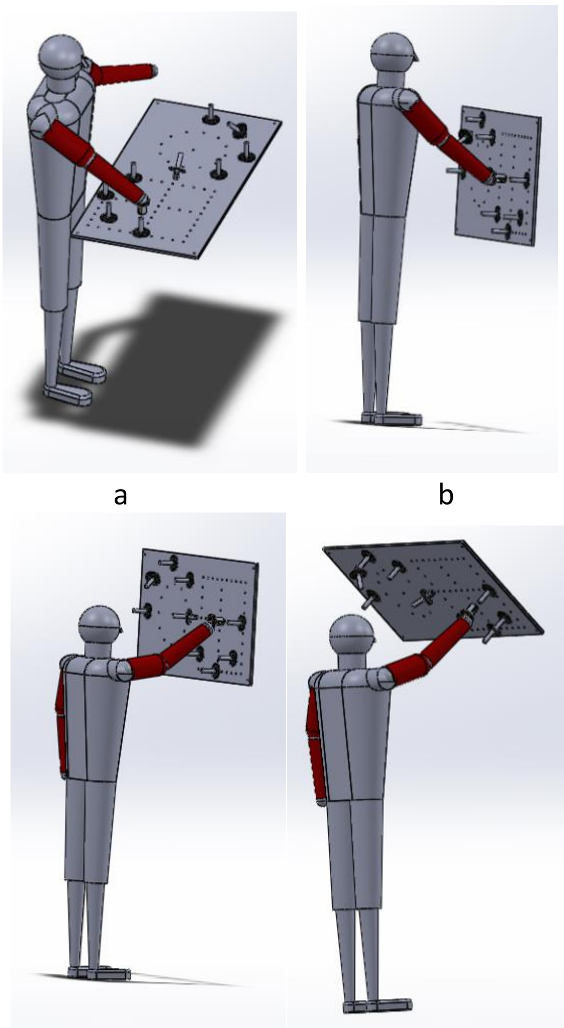
Similarly, wearable robot navigation tests can also be performed using response robot artifacts and methods. For example, inclined planes, undulating floors, stairs, and various complex terrains such as sand, gravel, or wet floors can be navigated while avoiding obstacles in the path.

Docking

Wearable robots or passive exoskeletons that allow human arms to move and hold tools for longer periods of time at intended locations could be measured using the RMMA. The human can instead carry a laser retroreflector or insert pegs in holes on such an artifact using a variety of geometric patterns and RMMA configurations. Also, similar to the mobile manipulator, as shown in Figure 3, fiducials detectable by an optical tracking system can measure the wearable robot motion if higher precision measurement data is required. This fine motion detection data can be used to further refine wearable robot motor tuning.

Figure 6 depicts the same RMMA, previously described for measuring performance of industrial robot arms and mobile manipulators, being used to measure the performance of an exoskeleton. The figure shows a human wearing arm exoskeletons and aligning a laser retroreflector to reflectors. The same RMMA could instead include holes in which the human could insert pegs or screws as potentially required for precision assembly applications. The RMMA is shown in (a) horizontal, (b) vertical-low, (c) vertical-high, and (d) over-head-angled configurations.

Both navigation and docking can be combined for full-body exoskeleton (i.e., legs and arms) access and dexterity tests. For example, the human in exoskeleton would repeatedly move from a different location to the RMMA, similar to tests for the mobile manipulator. Once at the RMMA, the same docking test would be administered. The results of this test could show the time for a human, wearing leg and arm exoskeletons, to repeatedly move to and be positioned to reach the RMMA (using leg exoskeletons) followed by the time to transition from full-body motion to arm-only motion (using arm exoskeletons) when controlled by the exoskeleton.



a b c d

Figure 6. Graphics of a human wearing arm exoskeletons (red) testing its performance using the RMMA for precision assembly applications when the RMMA is in (a) horizontal, (b) vertical-low, (c) vertical-high, and (d) overhead-angled configurations.

Dynamic tests can also be administered with the RMMA moving relative to the human and the same alignment task performed as previously described. Additionally, both the human with exoskeleton and RMMA can be moving while alignment or peg insertion tasks are performed.

<u>Grasping</u>

Grasping tests for hand exoskeletons are very similar to advanced robot gripper tests where various objects are picked up and manipulated (e.g., rolled, yawed, pitched) in the hand using fingertips and/or the palm and placed (e.g., set on a surface, inserted into a mating hole). Four grasp tests described in [25] and performed on the exoskeletons shown in Figure 7 are: 1) power grip, 2) two finger pinch, 3) three finger pinch, and 4) lateral pinch. The following are examples of more specific hand exoskeleton tests:

- a key could be picked up, inserted into a keyhole, and rotated,
- a ball is picked up, grasped using the fingers and palm, moved using only the fingers to the finger tips, and then rolled using only the fingertips,
- varying diameter bars each attached to a spring, or thin to thick ropes each attached to a weight, is grasped and pulled and force is measured,

- a doorknob is grasped with the hand and rotated using the wrist and/or a hand-wheel is grasped with the hand and rotated using the wrist and arms,
- a needle is threaded or a wrist watch-size gear is placed on a post and meshed with other similar-sized gears,
- repeated exercise of fingers followed by performing the above tests.

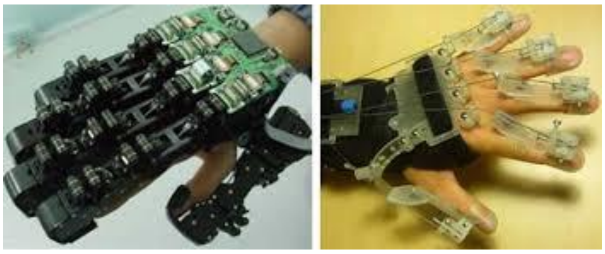


Figure 7. Example hand exoskeletons (courtesy Politecnico di Torino) [24].

6 Conclusions

Much experience in the development of metrics and test methods for the manufacturing and response applications can be applied to wearable robots. Manufacturing robotics are moving towards human-robot collaboration and response robotics is moving towards robot deployment instead of people. Test methods for both robot types are being developed to measure their performance and match it to the task at hand. Similarly, active exoskeletons are worn by humans to move body parts and passive exoskeletons are already being used to allow humans to extend their productivity and endurance. Safety standards now allow both manufacturing and wearable robots to be used. However, performance standards for both systems are still lacking. Test methods that are being or that have been developed for manufacturing and response robots can be directly applied to wearable robots as described in this paper. Nearly direct cross-over between these industries appears feasible and associated performance standards can also be developed for wearable robots. Future research should include demonstration and testing of wearable robots using similar test methods as that of manufacturing and response robots.

References

[1] Wolff, J., Parker, C., Borisoff, J., Mortenson, W. B., & Mattie, J. (2014). A survey of stakeholder perspectives on exoskeleton technology. Journal of NeuroEngineering and Rehabilitation, 11, 169. http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3304563/.
[2] Upper body exo: David Szondy, "Harmony rehab robot guides recovery", http://www.gizmag.com/harmony-rehab -robot/37293/ , May 4, 2015.
[3] Jessica Leber, "A Wearable Robot Suit That Will Add Power To Your Step", http://www.fastcoexist.com/3035535/a-wearable-robot-suit-that-will-add-power-to-your-step, September 11, 2014.
[4] Brady Dale, "A new industry flexes its servos", http://fortune.com/2014/08/27/exoskeletons-wearable-robotics/, August 27, 2014.
[5] Patrick Tucker, "The Very Real Future of Iron Man Suits for the Navy", http://www.defenseone.com/technology/2015/01/very-real-future-iron-man-suits-navy/102630/, January 12, 2015.
[6] Liz Stinson, "Navy's Exoskeleton Could Make Workers 20 Times More Productive", http://www.wired.com/2014/09/navys-exoskeleton-could-make-workers-20-times-more-productive/, September 10, 2014.
[7] Roger Bostelman, "International Standards Efforts Towards Safe Accessibility Technology for Persons with Disabilities: Cross-Industry Activities", Standards Engineering Society Journal, August 24, 2010.
[8] Hugh Herr, "Exoskeletons and orthoses: classification, design challenges and future directions", Journal of NeuroEngineering and Rehabilitation, 6:21 doi:10.1186/1743-0003-6-21, 18 June 2009
[9] Fryman, Jeff, and Björn Matthias. "Safety of industrial robots: From conventional to collaborative applications." In Robotics; Proceedings of ROBOTIK 2012; 7th German Conference on, pp. 1-5. VDE, 2012.
[10] Jacoff, Adam and Elena Messina, "Experiences in deploying test arenas for autonomous mobile robots", Performance Measurement for Intelligent Measurement

Systems (PerMIS), National Institute of Standards and Technology Special Publication 982, Gaithersburg, MD, USA, September 2001
[11] Glenn McDonald, “'Aliens'-Style Exoskeleton Gives Shipbuilders a Boost,” http://mashable.com/2014/08/05/daewoo-exoskeleton/, Discovery News, Aug 05, 2014.
[12] Performance of Collaborative Robot Systems Project, http://www.nist.gov/el/isd/ms/pcrs.cfm, 2015.
[13] Robotics Test Facility, http://www.nist.gov/el/isd/ms/roboticsbldg.cfm, 2014.
[14] International Organization of Standards (ISO), www.iso.org, 2015.
[15] Robot Industry Association (RIA), www.robotics.org, 2015
[16] American National Standards Institute/Industrial Truck Standards Development Foundation (ANSI/ITSDF), www.itsdf.org, 2015.
[17] ASTM International Committee E54, http://www.astm.org/COMMITTEE/E54.htm, 2015.
[18] Roger B. Bostelman, Tsai H. Hong, and Elena Messina, “Intelligence Level Performance Standards Research for Autonomous Vehicles”, International Robot Systems (IROS) 2015, Hamburg, Germany, September 2015.
[19] Roger Bostelman, Joe Falco, “Survey of Industrial Manipulation Technologies for Autonomous Assembly Applications”, NIST Internal Report 7844, March 16, 2012.
[20] Roger Bostelman, “International Standards Efforts Towards Safe Accessibility Technology for Persons with Disabilities: Cross-Industry Activities”, Journal of the Standards Engineering Society, August 24, 2010
[21] Johns Hopkins University Applied Physics Laboratory, http://www.jhuapl.edu/newscenter/pressreleases/2007/070426.asp , 2010.
[22] Joe Falco, Jeremy Marvel, Elena Messina, “A Roadmap to Progress Measurement Science in Robot Dexterity and Manipulation”, NIST Internal Report, 7993, March 2014.
[23] J. Falco, K. Van Wyk, S. Liu, S. Carpin, “Robotic Grasping: Facilitating Replicable Performance Measures via Benchmarking and Standardized Methodologies”, IEEE Robotics and Automation Magazine, December 2015.
[24] Performance Metrics and Benchmarks to Advance the State of Robotic Grasping, http://www.nist.gov/el/isd/grasp.cfm, September 2015.
[25] Alain Favetto, Elisa Paola Ambrosio, Silvia Appendino , Alessandro Battezzato , Fai Chen Chen , Diego Manfredi, Mehdi Mousavi, Francesco Pescarmona, "Embedding an Exoskeleton Hand in the Astronaut’s EVA Glove: Feasibility and Ideas", International Journal of Aerospace Sciences, Vol. 1 No. 4, 2012, pp. 68-76. doi: 10.5923/j.aerospace.20120104.03.
[26] Sarakoglou, Ioannis, Darwin G. Caldwell, Nikolaos G. Tsagarakis, and Sophia Kousidou. “Exoskeleton-based exercisers for the disabilities of the upper arm and hand”. INTECH Open Access Publisher, 2007.
[27] Messina, E. et al., “Statement of requirements for urban search and rescue robot performance standards,” http://www.nist.gov/el/isd/ms/upload/Prelim_Requirements_Report.pdf, 2005.

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