INTERNATIONAL STANDARDS EFFORTS

TOWARDS SAFE ACCESSIBILITY TECHNOLOGY FOR PERSONS WITH DISABILITIES:

CROSS-INDUSTRY ACTIVITIES

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1. Introduction

a. US Government Accessibility Standards Activities

Because of their large potential impact, accessibility standards might be thought of by many as only including the US Department of Justice Rehabilitation Act Section 508 standard or the Americans with Disabilities Act (ADA) standards. Section 508 requires that electronic and information technology that is developed by or purchased by the Federal Agencies be accessible to people with disabilities. [1] The ADA standard part 36 of 1990 (42 U.S.C. 12181), prohibits discrimination on the basis of disability by public accommodations and requires places of public accommodation and commercial facilities to be designed, constructed, and altered in compliance with the accessibility standards established by this part. [2] Other US Federal Government agencies have ADA responsibilities as listed here with the regulating agency shown in parentheses:

- Consider Employment (Equal Employment Opportunity Commission)
- Public Transportation (Department of Transportation)
- Telephone Relay Service (Federal Communications Commission)
- Proposed Design Guidelines (Access Board)
- Education (Department of Education)
- Health Care (Department of Health and Human Services)
- Labor (Department of Labor)
- Housing (Department of Housing and Urban Development)
- Parks and Recreation (Department of the Interior)
- Agriculture (Department of Agriculture)

Like the agencies listed, the US Department of Commerce, National Institute of Standards and Technology's (NIST) supports and complies with the 508 and ADA standards. Moreover, NIST was directed by the Help America Vote Act of 2002, to work with the Election Assistance Commission (EAC) and Technical Guidelines Development Committee (TGDC) to develop voting system standards - Voluntary Voting System Guidelines (VVSG). [3] NIST also supports healthcare standards due to the rapid development of personal care and medical robots that is driving the need for safety standards. New international standards are now being written to ensure the safe manufacture and use of these robotic systems.

b. Healthcare and Manufacturing Standards Crossover Activities at NIST

The NIST Manufacturing Engineering Laboratory's Intelligent Systems Division (ISD) program called Measurement Science for Manufacturing Robotics and Automation [4] researches human/robot collaboration for manufacturing. Current safety standards suggest industrial robot arms and vehicles are not safe enough to be used around humans. However, manufacturers envision future benefits if humans can work side-by-side with robots in flexible and efficient workspaces. Robotic vehicles and arms having direct human/robot interaction are currently being developed for the healthcare industry. ISD is, therefore, researching standards and performance measurements for the healthcare industry in parallel with the manufacturing industry. Two specific areas of healthcare standards research at NIST with crossover to the manufacturing industry are: 1) wheelchair safety standards for advanced wheelchairs that are intended to help persons with disabilities be independent and 2) a new international personal care robots safety standard. These form the main subject of this paper.

ISD is applying similar technology across both the healthcare industry, including wheelchair, patient hoist and prosthetics technologies, and the manufacturing industry (rolling and suspended) material handling and robot arm technologies. Healthcare industry standards include:

- International Organization for Standards (ISO) [5] 7176 Wheelchairs and its many parts,
- ISO 10535 Hoists for the transfer of disabled persons,
- Australian AS 3581 Mechanical Aids [6],
- Technical Committee 168 class of ISO standards of prosthetics and orthotics
- and the recent ISO 13482 Robots in personal care (including healthcare) standard.

ISD exchanged information from these healthcare standards with manufacturing industry standards, including for example:

- European Standards (EN) 1525 and American National Standards Institute (ANSI) [7] B56.5 Safety of industrial trucks,
- American Society of Mechanical Engineers (ASME) [8] B30.23 Personnel Lifting Systems,
- ISO 9928 Cranes, and ISO 10218 Robots for industrial environments.

Examples of standards being applied across industries include:

- text from the ANSI B56.5 standard was also suggested for use in ISO 13482 with regards to vehicle braking;
- ISO 10218 and ANSI/RIA 15.06 industrial robot arm safety standards are being used to help formulate parts of ISO 13482 dealing with safety around humans;
- ISO 9928 crane load hoisting being applied to a forklift in an advanced NIST wheelchair concept;
- ISO 7176 static and dynamic wheelchair stability tests being applied to an advanced wheelchair and also to a concept for a semi-autonomous person-sized forklift technology.

The outcome of these ISD standards efforts is expected to make a global impact for the disabled.

2. Accessibility to Home Amenities for Persons with Disabilities

a. Technology Needs

Caregivers and nurses often have to lift patients and seat them in wheelchairs, beds, or automobiles. It is estimated [10] that one out of every two non-ambulatory patients falls and becomes injured while being transferred from a bed to a wheelchair. In addition, one in every three nurses becomes injured from the physical exertion of moving non-ambulatory patients. According to current statistics, the number of people in the United States, 65 years or older, will double in the next 25 years. In 1950, there were 8 adults available to support each person 65 or older. Today, the ratio is 5:1 and by 2020 this ratio will drop to 3 working age adults per elderly person. As a person ages, independence remains an important factor in his or her life. According to U.S. researchers, elderly individuals increase the possibility of remaining independent by 41 percent when they exercise regularly (e.g., walking). Remaining independent and healthy typically requires devices that allow accessibility for the disabled to the same home amenities and areas that the able have access to. However, these devices are usually single purpose and still might require assistance from a caregiver.

A survey conducted by NIST showed that there is a need for devices that provide mobility, lift, and can transfer patients so that subjects can reach upper shelves, or be placed on toilets, chairs, beds, and bathtubs [11]. Mobility devices include manual and powered chairs and scooters with power-assisted manual wheelchairs. The literature survey showed that mobility devices today are not combined with patient transfer/lift devices or rehabilitation devices. In most cases, this technology comes in the form of a powered chair with a seat lift axis still requiring the patient to keep their feet on the device and not on the floor. Therefore, rehabilitation to allow the potential for the patient to walk and exercise their legs is non-existent with today’s devices. For patients that are less mentally aware and immobile, powered chairs are not useful. Intelligent (robotic) mobility is being researched [11] where algorithms are applied to powered chairs to enable a patient to move autonomously. These intelligent devices have made excellent strides toward a robotic chair, e.g., to improve mobility of patients with severe and multiple disabilities through cluttered environments with graphical user interfaces. However, these chairs do not facilitate without patient transfer. Individual mobility devices, transfer devices, or rehabilitation devices are commercially available, some operated by caregivers and some by patients. All of the mobility devices researched utilized off-the-shelf powered chairs without onboard patient lift, patient transfer, or rehabilitation capabilities.

Dependent care patient lift devices include manual and powered hydraulic rolling beds and chairs. These typically require the following user actions: patient pivots out of the chair, patient stands, patient’s sling is attached to a sling lift or a rolling lift mounted to a wall, bed or ceiling. Independent care patient lifts include: trapeze-style, ceiling-mounted cable lifts, stair lifts, wheelchair-to-vehicle lifts and some automobile-mounted patient lift devices. All of these devices provide only a part of the lift required by the patient. Also, many of these lift devices require significant patient and/or caregiver strength. A combination patient lift, mobility, positioning and rehabilitation device is therefore needed. Additionally, measurements of such combined use devices are non-existent and yet could provide recommended changes to existing international safety standards.

b. NIST Home Lift, Position and Rehabilitation (HLPR) Chair

The information presented in the Technology Needs section led to the design of the NIST Home Lift, Position and Rehabilitation (HLPR) Chair [12], [13]. Two prototypes, called HLPR Chair 1 and 2, were designed and built based on cross-industry technology from manufacturing forklifts. HLPR Chair 2 is shown in Figure 1 displayed at the 2008 Safe Patient Handling and Movement Conference and Exhibition in Orlando, FL.

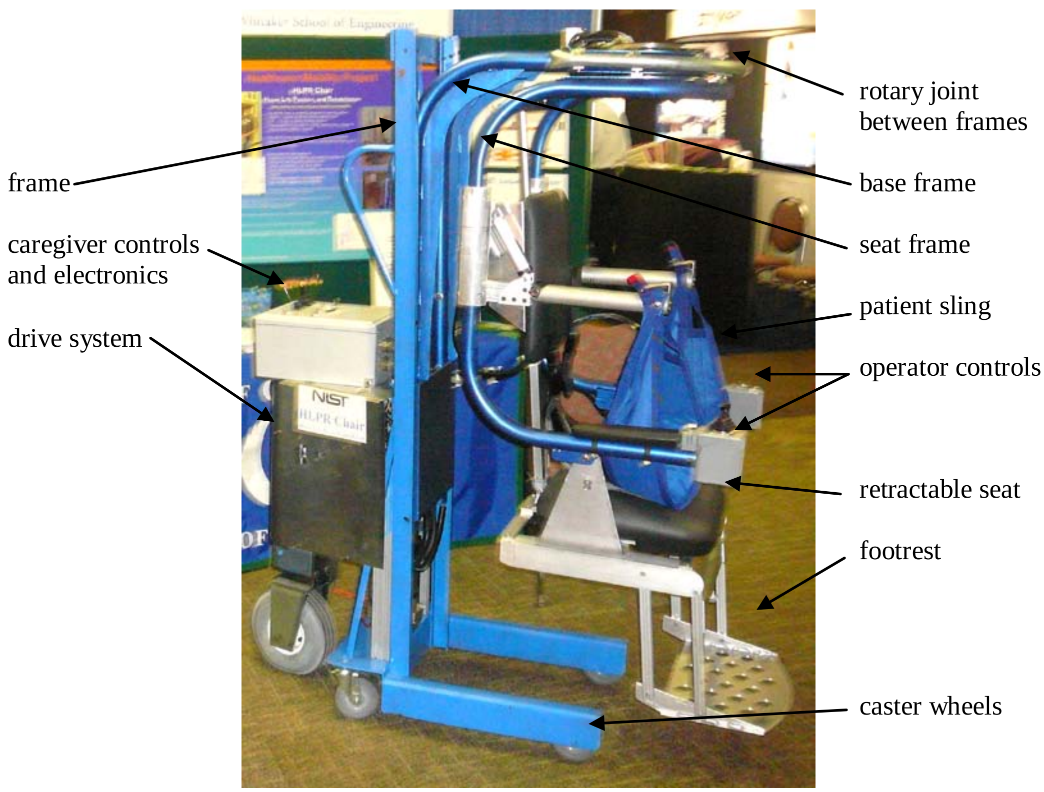
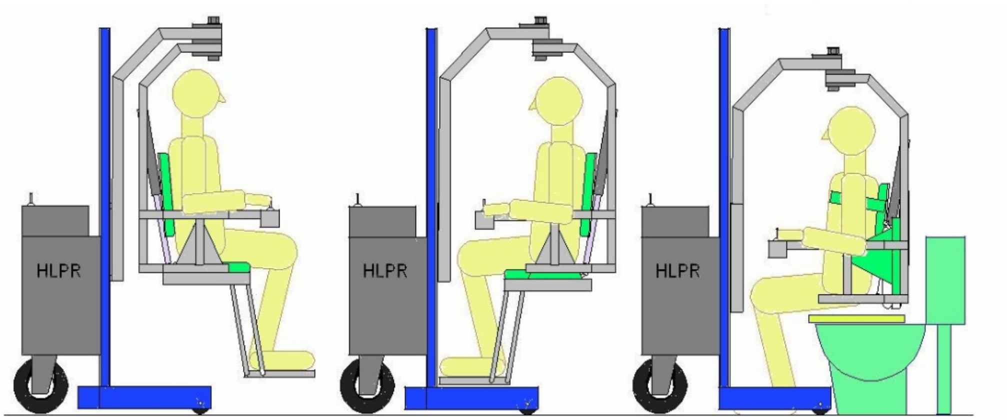


Figure 1 – HLPR Chair being exhibited at the Safe Patient Handling and Movement Conference, Orlando, FL, March 2008.

Figure 2 shows how the HLPR Chair can position a patient onto or from a toilet or other seat. With the HLPR Chair, immobile persons would also be able to transfer themselves onto a seat or bed; lower themselves to remove dishes from the dishwasher and raise themselves to put the dishes onto the top shelf of a cupboard. All basic functions of patient lift, mobility, positioning and rehabilitation have been demonstrated and appear in a video downloadable from [9]. The patient or a caregiver can control the HLPR Chair. Additionally, the HLPR Chair can be autonomously controlled through an onboard computer as was demonstrated in the laboratory and described in [13].



a b c

Figure 2 – HLPR Chair transferring a patient to a toilet: a) footrest has been retracted beneath the seat and the patient is approaching the toilet, b) seat frame with patient have been rotated and the seat is retracting, and c) HLPR approaches and the patient is lowering to the toilet seat.

c. Current Wheelchair Standards

International wheelchair safety standards are only recently considering wheelchairs beyond manual types. The unique shape (see Figure 3) and capabilities of the HLPR as compared to typical wheel- and powered chairs requires examination of its stability. Existing standards do not adequately cover this design. Unique characteristics of the HLPR chair that are not included in current standards are: 1 m lift, seat rotation, and two casters with single wheel drive-and-steer wheel design with stabilizers.

Figure 3: Typical powered chair (left) [courtesy Jazzy[1]] and the HLPR Chair 1 prototype (right three photos). HLPR Chair is shown in the mobility (center photos) and the lift (right-most) configurations. Note the unique shape of HLPR Chair as compared to typical powered chairs.

As a load-carrying device, the frame and wheelbase closely resemble a walk-behind forklift. For this reason, ANSI/RESNA and ISO standards for wheelchairs and forklifts were consulted to assess the stability of the HLPR under both static and dynamic conditions. The standards referenced for these stability tests were and are searchable in the ISO, Australian and ANSI websites referenced previously:

- International Standard IS0 7176-1:1999 (E) Wheelchairs – Part 1: Determination of static stability [5]
- International Standard IS0 7176-2: 2001 (E) Wheelchairs – Part 2: Determination of dynamic stability of electric wheelchairs
- International Standard IS0 7176-7:1998 (E) Wheelchairs – Part 7: Measurement of seating and wheel dimensions
- International Standard IS0 7176-10:1998 (E) Wheelchairs – Part 10: Determination of obstacle-climbing ability of electric wheelchairs

[1] Certain commercial equipment, instruments, or materials are identified in this report in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

- International Standard IS0 7176-11:1992 (E) Wheelchairs – Part 10: Test dummies, first edition 1992-05-01
- International Standard IS0 7176-22:2000 (E) Wheelchairs – Part 22: Set-up Procedures, first edition 2000-05-15
- International Standard IS0 1074: 1991 (E) Counterbalanced fork-lift trucks – Stability tests
- Australian Standard AS 3581-1988, Mechanical Aids for Patient Lifting and Moving – Safety Requirements [6]
- American National Standard ANSI for Wheelchairs – Volume 1: Requirements and Test Methods for Wheelchairs (Including Scooters) [7]
- American National Standard ANSI for Wheelchairs – Volume 2: Additional Requirements for Wheelchairs (Including Scooters) with Electrical Systems

Stability test methods were developed with consideration of HLPR's transition from an intelligent powered and lift wheelchair to a load-carrying and lift device for the manufacturing industry. In the case of existing and similar standards for wheelchairs and forklifts, the most rigorous test was adapted. The purposes of the stability tests were to determine the maximum safe load capabilities, the maximum safe angles of operation, and the braking capabilities of the HLPR.

d. Suggested Changes to Wheelchair Standards

ISD performed static and dynamic stability safety tests using the HLPR Chair 1 prototype. [14] HLPR stability was evaluated based on the ANSI and ISO wheelchair and forklift standards. Figure 4 shows the test operator performing one of several static tests and Figure 5 shows the test operator ready to perform one of many dynamic stability tests on a sloped surface.

Based on the HLPR chair stability tests, new test methods were created and tested that are currently not provided in the above listed standards because of HLPR's unique lift and rotation capabilities. The modifications listed in Table 1 would enhance current standards to support devices built now and in the future that have similar characteristics to the HLPR Chair.

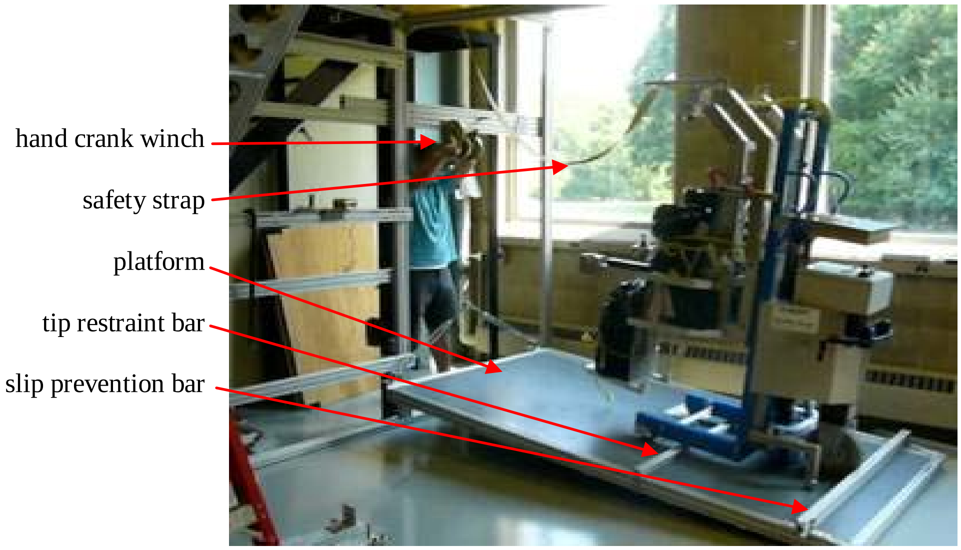


Figure 4 - Stability test being performed on the HLPR Chair using a variable slope platform and safety devices.

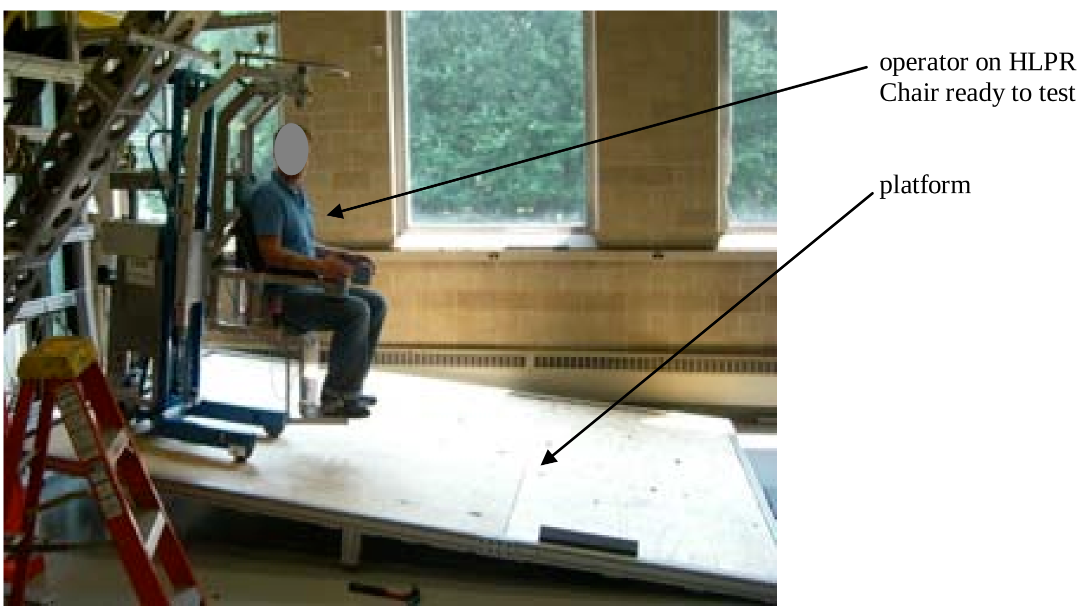


Figure 5 - HLPR chair dynamic stability test setup.

Table 1 – Suggested Standards to be Changed Based on HLPR Chair Stability Tests

Standard to be advanced	Suggested Advancement to Standards
ISO 7176-1 Wheelchairs Sections 9, 10, 12	Currently no listing for seat rotation, therefore add methods for testing with rotated seats in the forward, rearward, and sideways orientation with seat rotation in the least and most stable positions.
ISO 7176 – 22 Wheelchairs	Currently, seat rotation is not listed, nor set-up procedures and recording of measurements and settings. Insert these parameters.
ISO 7176 Part 1	Section 3.2 tipping angle test is currently difficult to perform with a single test operator. A better method is suggested.
ANSI/RESNA WC/Vol. 1-1998 and ISO 7176-1	Currently, these standards show a horizontal restraint bar. The bar only provides one axis of restraint and at only one height for existing devices. Instead, use an adjustable safety harness attached between hard points and the vehicle top.
ANSI/RESNA and ISO stability standards	Standing and walking with the current devices are not possible. For rehabilitation, future vehicles like HLPR Chair can provide this capability and the standard must allow safe operation in this configuration including standing and sitting slings attached to the device. Some industry standards that could potentially provide text are: • ASME / ANSI Standards. B30.2. Overhead Cranes • ANSI/ASME B30.9 – 1984 Slings • ASME B30.21 – 1982 Manual Lever Operated Hoists • ANSI/ITSDF B56.10 - 2006, Safety Standard for Manually Propelled High Lift Industrial Trucks • Occupational Safety and Health Administration (OSHA) 1910.67 or ANSI A92.2-1969 Vehicle Mounted Elevating and Rotating Work Platforms.

(No existing standard located)	These are tests that the researchers could not locate in current standards but may be useful to improve the safety of wheelchair operators: • need for seatbelts when a human rider is used in place of a test dummy. This is especially true of ISO 7176-2 dynamic stability testing where the device is restrained, but the rider is not. • test dummy leaning forward. This changes the center of mass for the rider and device, perhaps also changing stability test results. • autonomously-controlled wheelchairs could reference ANSI/ITSDF B56.5 Safety Standard for Driverless, Automatic Guided Vehicles and Automated Functions of Manned Vehicles.

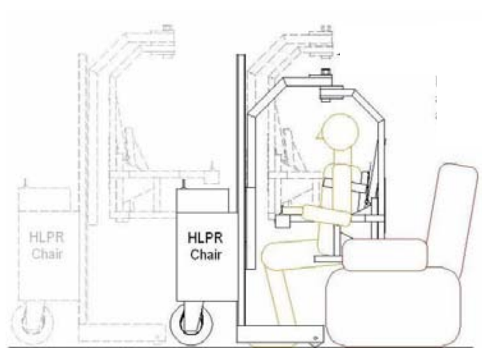
3. Personal Care Robot Standards Efforts

Personal care robots to improve accessibility of the disabled will soon be prevalent throughout the world as caregivers are becoming fewer, wars are creating combat amputees, and the world population is getting older. Time is of the essence to develop performance metrics and safety standards for personal care robots since this technology is already being marketed in Japan [15] and possibly in other countries as well. A new set of ISO 13482 standards is being developed to guide manufacturers to produce safe personal care robots. ISO 13482 will include parts for terminology, medical robots, personal care robots, and service robots (e.g., robot lawnmowers). ISO 13482 Robots in Personal Care (including healthcare) – Safety Standard – Part 1: Non-Medical Robots is to be completed in January 2012. The scope of ISO 13482 Part 1 is to specify requirements and guidelines for the inherent safe design, protective measures and information for use of non-medical personal care robots. It describes hazards associated with the use of these robots and provides requirements to eliminate or adequately reduce the risks associated with these hazards. ISO 13482 - Part 2, as currently named, is expected to be completed in approximately 2014 and will include medical robots that are both invasive and non-invasive to humans.

The author serves as a US expert on the ISO 13482 – Parts 1 and 2 working and study groups. NIST also provides input on manufacturing safety and performance standards, such as ANSI and ISO robot vehicle and arm standards, and/or by performing measurements on these robots. Specifically, ISD has impacted the standard with editorial and technical advances resulting from the HLPR Chair standards efforts and from industrial robot and vehicle performance measurements research. For ISO 13482, ISD has been tasked with developing the risk assessment tables for person carrier robots because of their industrial vehicle experience and safety standards efforts.

ISD suggested that a new ISO 13482 Annex C be considered to clarify the scope of the standard by providing the categories, types and functionalities of many different types of personal care robots. From the many categories suggested, three categories were identified by the committee: mobile servant, person carrier, and physical assistant robots. Most recently, ISD has been tasked to support Japan and Germany committee experts to develop the Annex C table and to develop risk assessment protocols for both vehicles and personal assistant robots, such as exoskeletons and other wearable robots. Table 2 shows an example of how the Annex might appear.

Table 2 – Example of the Suggested ISO 13482 Annex C Table.

Category	**Type**	**Function**	**Example figures**
person carrier robot	mobile person mover with manipulator robot	navigate, find, approach, support and/or interact with person(s) to directly hold, serve and manipulate person(s), e.g., deliver person(s) and perform specific tasks including person lift, deliver, hold, place, transfer	

The table shows an example of a robot like the HLPR Chair providing accessibility for a disabled person to typical cushioned chairs. ISD suggested that autonomy levels for robots be included in the standard based on NIST research [16] for each robot type and may appear in later, more detailed versions of the standard. The following sections detail additional ISD efforts in the person carrier and wearable robot areas.

a. Person Carrier Robots

Automated guided vehicles (AGVs) are used to autonomously pull or carry relatively heavy loads throughout manufacturing and distribution facilities. AGVs now use non-contact sensors for obstacle/human detection although AGV paths are typically separated from walkways. Many AGV users would like humans and AGVs to work in shared spaces.

ISD performed measurements using AGV safety sensors and advanced non-contact sensors on standard-sized test pieces for the ANSI B56.5 Industrial Truck Safety Standard. Test pieces within the B56.5 standard are similar to human leg and body profiles and are also suggested as test pieces for the ISO 13482 standard non-contact safety sensor tests. Additionally, tests for braking, control, stopping distance, contact forces, loss of power, and surface conditions are all suggested for ISO 13482 risk assessment sections based on B56.5 standard text. Moreover, HLPR Chair stability measurement improvements suggested to improve ISO 7176 Wheelchair testing are suggested for inclusion in ISO 13482 risk assessment hazards and mitigation.

b. Wearable Robots - Exoskeletons and Prosthetics

Wearable robots, such as exoskeletons and prosthetics, are intended to provide increased mobility for the disabled. Exoskeletons are to be strapped onto the disabled and elderly and used to move and exercise human limbs to provide near-normal walking and lift functionality. They may even be used to help humans carry loads that are heavier than they can carry unassisted. Several researchers are already developing exoskeletons (see examples in Figure 6) that will allow disabled wearers to have improved accessibility. Prosthetics can also provide accessibility for persons with disabilities with today’s advances providing much more dexterity than ever before for humans missing limbs.

a b c

Figure 6 – Examples of exoskeletons being developed for persons with disabilities around the world: a) Cyberdyne Japan, b) Korea Institute of Science and Technology, c) University of Salford, in Manchester, England. [17]

Safety standards for these wearable robots are critical to minimize the risk of harm to the wearer and others. Crossing over to the manufacturing industry, ISD has been researching the safety of industrial robot arms when in close proximity to humans and is supporting the ISO 10218 Industrial Robot Safety standard through performance measurements and standards activities that include non-contact sensors integrated with robot arm control. In a German study [18], researchers are using crash dummies to support standards development of crash-testing protocols for robot safety. These combined efforts show the need for industrial robot safety standards to be advanced as humans and robots carry out activities in close proximity to each other. Similarly, from the healthcare industry perspective, ISO 13482 Parts 1 and 2 will include safety of wearable robots that could present risk to humans. ISD efforts on ISO 10218 are being considered for use in ISO 13482 with regard to risk assessment of humans near robots.

ISD has provided a list of exoskeleton risks to the ISO 13482 committee and is currently working with exoskeleton researchers from Lockheed Martin to assess the risks and devise mitigation procedures that commercial exoskeleton designers and wearers will need to follow. These risks include that the device: moves by itself while off or on the user, causes strain or stress to the user, exhibits electrical and mechanical failures, etc. All of these risks and their mitigation requirements have been defined by ISD and Lockheed and are suggested for inclusion into ISO 13482.

Similarly, ISD is working with the Defense Advanced Research Project Agency's (DARPA) Revolutionizing Prosthetics Program, including their two advanced arm designers and builders – DEKA Integrated Systems and Johns Hopkins University Applied Physics Laboratory – to assess new prosthetic arm risks and establish risk mitigation requirements for manufacturers. Since there are autonomous functions in new prosthetics, there is potential risk to advanced prosthetic robotic arm wearers and to those nearby. Therefore, ISD has suggested that results of these joint efforts on risk assessment be included in ISO 13482. Figure 7 shows an older wearable (non-invasive) and a newer DARPA (non-invasive or invasive) prosthetic arm.

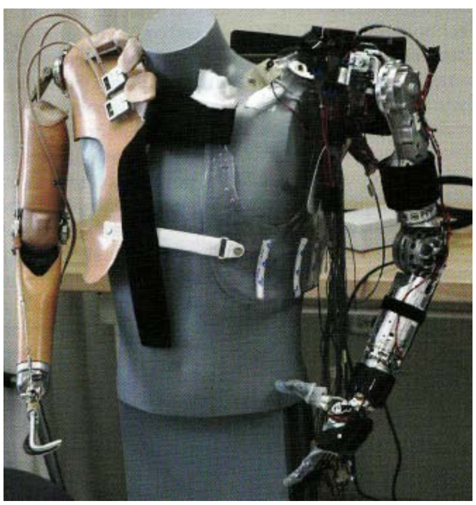


Figure 7 – Mannequin showing (right arm) traditional body-powered prosthetic arm technology with hook end effecter and (left arm) an initial prototype of a robotic arm technologies with fully functional arm and hand. [19]

In [20], Kumar, et. al. state that "industrial robots currently lack dexterity in their end-effectors and hands." Unfortunately, the same is evident with current prosthetic arm attachments where interchangeable end effectors are sometimes provided for the wearer but most arms simply don't provide the necessary dexterity to perform the whole variety of typical daily tasks. For example, as shown in Figure 8 (a and b), an end effecter used for playing baseball would be very difficult for use to drive a car and vice versa. Also, "existing prosthetic devices provide very little sensory feedback." [21] The DARPA advanced prosthetic arm program aims to conform technology development for the combat amputee who has lost a hand or arm, to meet human capabilities of dexterity and general use (see Figure 11 (c)). These new devices will soon have tactile sensing, a human hand-like grip and dexterity, and will be able to limit gripping forces on objects.

a b c

Figure 8 – (a and b) Samples of various prosthetic arm attachments a) split hook, b) prehensor, [22] and (c) an advanced highly dexterous robotic hand being developed [23]

ISD is working to foster transfer of healthcare dexterous manipulation technologies, such as DARPA's efforts, to solve manufacturing robotics challenges for autonomous assembly applications that require highly dexterous manipulation. This benefits both the manufacturing and healthcare industries, with standards overlap between ISO 13482 Parts 1 and 2 for safe advanced prosthetic robot arms with high dexterity and ISO 10218 for safe advanced highly dexterous manipulation for industrial robots.

4. Conclusions

Multiple federal government agencies are developing standards for improved accessibility for persons with disabilities. NIST ISD seeks to enhance accessibility for persons with disabilities through standards that cross over between healthcare and manufacturing industries. The efforts include the development and performance testing of the HLPR Chair, studying manufacturing and healthcare industry robot vehicles and arms, and supporting the DARPA Revolutionizing Prosthetics Program among other efforts. These combined efforts are showing huge impact for developing the new ISO 13482 standards set and ISO 10218 standards for safe human robot collaboration. These standards are gaining increased international interest with for example, five participants supporting the 13482 standards committee in the beginning to 28 participants at the recent meeting in France, representing 8 countries. There are already personal care robots and medical robots that provide improved accessibility for humans and there will be many more in the future. The rapid development of personal care and medical robots is driving the need for safety standards. New international standards are now being written to ensure the safe manufacture and use of these robotic systems.

5. References

[1] US Department of Justice Rehabilitation Act Section 508 standard, http://www.section508.gov/.

[2] Americans with Disabilities Act http://www.ada.gov/reg3a.html, January 22.

[3] NIST and the Help America Vote Act, http://vote.nist.gov, April 23.

[4] Measurement Science for Manufacturing Robotics and Automation Program website, http://www.nist.gov/mel/isd/si/msimra.cfm, 2010.

[5] International Organization for Standards, http://www.iso.org/iso/iso_catalogue.htm.

[6] AS 3581-1988, Mechanical Aids for Patient Lifting and Moving – Safety Requirements, 1988.

[7] American National Standards Institute website, http://www.ansi.org/, 2010.

[8] American Society of Mechanical Engineers website, http://www.asme.org/.

[9] NIST Healthcare Mobility Project, http://www.isd.mel.nist.gov/healthcaremobility/concepts.html, November 21, 2007.

[10] Bostelman, Roger; Ryu, Ji-Chul; et. al., "An Advanced Patient Lift and Transfer Device for the Home," Journal of Medical Devices, Transactions of ASME, Vol. 4 / 011004-1 to 011004-8, March, 2010.

[11] Bostelman, R. and Albus, J., Survey of Patient Mobility and Lift Technologies Towards Advancements and Standards, NISTIR No. 7384, 2006.

[12] Bostelman, Roger; Albus, James; “HLPR Chair – A Service Robot for the Healthcare Industry,” 3rd International Workshop on Advances in Service Robotics, Vienna, Austria, July 7, 2006.

[13] Bostelman, Roger; Albus, James; “Robotic Patient Transfer and Rehabilitation Device for Patient Care Facilities or the Home,” Journal of Advanced Robotics, Vol. 22, 1287–1307.

[14] Johnson, Joshua; Bostelman, Roger; “Static and Dynamic Stability Performance Measurements of the HLPR Chair/Forklift,” NIST Interagency/Internal Report (NISTIR) – 7667, March.

[15] “Honda unveils robotic legs that could improve people's mobility,” http://www.news.com.au/technology/honda-unveils-robotic-legs-for-humans/story-e6frfro0-1111117975611, November 7.

[16] Hui-Min Huang, Kerry Pavek, James Albus, Elena Messina, “Autonomy Levels for Unmanned Systems (ALFUS) Framework: An Update,” 2005 SPIE Defense and Security Symposium, Orlando, FL, 2005.

[17] IEEE Spectrum – Exoskeletons around the world pictorial website, http://spectrum.ieee.org/robotics/medical-robots/exoskeletons-around-the-world/0, 2010.

[18] Sami Haddadin, Alin Albu-Schaffer, Mirko Frommberger, Jurgen Rossmann, and Gerd Hirzinger, "DLR Crash Report: Towards a Standard Crash-Testing Protocol for Robot Safety," Proc. 2009 IEEE International Conference on Robotics and Automation, Kobe, Japan, 2009.

[19] Colinger, Jennifer, Grindle, Garrett, et. al., "Road Map for Future Amputee Care Research," Care of the Combat Amputee, Textbooks of Military Medicine, 2009.

[20] Kumar, Vijay; Bekey, George; and Zheng, Yuan, “WTEC Panel on International Assessment of Research and Development in Robotics, Final Report,” January 2006.

[21] Sensinger, Jonathon; Pasquina, Paul; Kuiken, Todd; "The Future of Artificial Limbs," Care of the Combat Amputee, Textbooks of Military Medicine, 2009.

[22] Radocy, Robert, "Upper Limb Prosthetics for Sports and Recreation," Care of the Combat Amputee, Textbooks of Military Medicine, 2009.

[23] Johns Hopkins University Applied Physics Laboratory,
http://www.jhuapl.edu/newscenter/pressreleases/2007/070426.asp , 2010.