Test Methods for Exoskeletons – Lessons Learned from Industrial and Response Robotics

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Abstract: Exoskeletons are devices that can assist the human wearer's limbs to provide functional, normal, or amplified human capabilities. Research on exoskeletons has dramatically increased recently. However, measurements of these devices have yet to show long-term safety and other effects on humans. Safety standards now allow, through risk assessment, both manufacturing and wearable robots to be used, although performance standards for both systems are still lacking. Much can be learned from industrial and response robot safety and performance research and standards activities that can cross over into the exoskeleton arena. For example, 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 chapter first lists exoskeleton performance metrics and standards for collaborative industrial robots, response robots, and also physical assistance robots (i.e., exoskeletons). Then it describes measurements of joint axis rotation location using an industrial robot simulating a human arm, as well as mobile manipulator and response robot test method developments that could also apply to exoskeletons. These methods and others are then integrated into recommendations for exoskeleton test methods.

Key words: exoskeleton, cross-industry, industrial robot, response robot, artifact, standards

1. Introduction

Exoskeletons[1] (e.g., wearable robots, passive, counterweighted) are devices that can assist the human wearer's limbs to provide functional (i.e., perhaps below normal), normal, or amplified human capability. Both passive (spring-supported and/or counterweighted) and active (electrically powered) human-worn devices are considered as exoskeletons. Capabilities provided by these devices include normal human lifting and/or other movements for extended time periods, for example, typical and beyond typical work days, as well as increased human strength, speed, agility, etc. for amplified exoskeleton versions. Recent research on exoskeletons has dramatically increased as seen in, for example, [1] and [2], and has driven the current global exoskeleton market to include over fifty manufacturers. However, performance, ergonomic, healthcare impacts, long-term safety, and other effects on humans have yet to be studied and understood.

International Organization for Standardization (ISO) 13482 [3] was developed over several years and published in 2014 to address the safety concerns for robots, including exoskeletons, used as personal care devices. Medical exoskeletons, such as those for rehabilitation, are not considered here. However, no normative requirements on data collection and analysis are included in the safety standard to be used as a basis for understanding long-term effects. Test methods that formalize means of collecting and analyzing

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[1] Disclaimer: Commercial equipment, software, and materials are identified in order to adequately specify certain procedures. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials, equipment, or software are necessarily the best available for the purpose.

performance data are therefore needed that allow manufacturers and users to replicate standard safety procedures in a uniform manner. The data from these test methods will enable the understanding of the ramifications from use of exoskeletons. Exoskeleton performance is interlaced with some safety considerations for these devices. For example, what are the issues when an exoskeleton is applied to the lower extremity (e.g., legs and hips) to assist or augment a human in carrying out tasks? As an exoskeleton user stands up from a crouched position or walks for an entire day carrying heavy loads, does the device provide full lift, overdrive human joints, cause the wearer strain or chafed skin, or other harm and if so, how should the device instead be designed to be safe? Safety test methods can help provide this measured data for most any exoskeleton manufacturer for comparison of capability to perform the task. However, performance test methods may additionally provide task-specific measurements of how well the device can provide, for example, improved movement, increased or longer lift capability, or combined lift with precision positioning of a heavy load. Unfortunately, there are currently no performance standards or test method procedures to provide such exoskeleton measurement data to be included in either safety or performance standards when they are developed. In addition, there are no commonly agreed upon physiological measurements of the human user to provide baseline measurements of before and after long term use of exoskeletons.

The National Institute of Standards and Technology (NIST), Robotic Systems for Smart Manufacturing (RSSM) Program [4] develops test methods and measurement science for stationary and mobile robot arms as well as vehicles to support calibration, measurement, and advance understanding of current and target performance of emerging new capabilities for manufacturing applications. The program develops and deploys advances in measurement science that enhance U. S. innovation and industrial competitiveness by improving robotic system performance to achieve dynamic production for assembly-centric manufacturing. NIST also has the objective to advance the capabilities of remotely operated emergency response robots by developing the measurement and standards infrastructure necessary to quantitatively evaluate system capabilities under the Emergency Response Robots Project. [5]

One example of the work being done under the RSSM program is the development of performance metrics and test methods for mobile manipulators that can be used for assembly. Assembly operations performed by a mobile manipulator require accurate position and orientation (pose) relative to a work piece, e.g., to insert pegs in holes or mesh gears with other gears. Advanced measurement tools and artifacts are being used at NIST to develop affordable and repeatable performance measurement and test methods. For example, test methods are being developed that can measure how well a mobile manipulator can align with a work piece so that the peg-in-hole operation can succeed. Another test method being developed can determine the exact location of industrial robot joints from outside the robot so that devices can properly adapt to robots.

Lessons can be learned from these industrial robot measurement methods to apply to exoskeletons where, as exemplified above, load positioning (versus pose of a peg held by a mobile manipulator) or human knee or elbow joint (versus external robot joint) measurement should be performed in a repeatable way. This and many other tests are required to fully understand how exoskeletons can maintain and/or improve human performance throughout an entire day and for many days.

This chapter initially provides a list of potential exoskeleton performance metrics which could be used as a basis for the development of test methods. The chapter then discusses current standards for collaborative industrial robots, response robots, and physical assistance robots (i.e., exoskeletons). The chapter then provides background, a literature survey, and description of experiments and results of joint axis location measurement using a robot arm simulating a human limb and an optical tracking system. The test method can also apply to measurement of the human knee or elbow rotational axis locations which are important to how well an exoskeleton fits to the human body. From these industrial/response robot test methods and experiments, recommendations for exoskeleton test methods are then considered, followed by a summary and conclusions.

2. Exoskeleton Performance Metrics

It is important to categorize performance metrics of systems-under-test to benchmark and compare results across systems, as well as to compare system applications to tasks. Industrial robot metrics currently typically do not include human(s)-in-the-loop since most robot functions are automatic and disconnected from human control. This is changing as collaborative robots that function side-by-side with humans are becoming available. Response robot metrics do include humans since the robots are mainly remotely controlled by humans and tasks may include finding and interacting with victims. From [6], we extract common metrics for task-oriented mobile robot human-robot interaction that may also apply to exoskeletons. Below, we provide their list and ask associated questions for each metric when applied to exoskeletons:

- Navigation: can the exoskeleton assist the wearer in remaining stable with a short or long stepping gait patterns, when walking, running, or even crawling if specified by the manufacturer, and also when normal gait activity is interrupted or various motion tasks initiated?
- Perception: can the exoskeleton access body measurements, perceive these inputs, and make use of the perceived input(s) to control the next intended motion(s)?
- Management of tasks: can the exoskeleton react to sudden obstacles, e.g., input sensory information from the body and then react appropriately to such emergency situations for avoiding collision or mitigate their effects?
- Manipulation: when using upper-body exoskeletons, can the robot move the arm appropriately for the task, both with and without loading and how does it change the user for when they are not wearing the robot?

Other effects, or what [6] termed as "bias effects," that perhaps adjust the above metrics are: communication (delay, jitter, and bandwidth), response from the robot (reaction to sensory input from the wearer), and the user (i.e., size, mass, profile, signal strength, expected signals). Further complicating matters, exoskeleton metrics that include the human-in-the-loop must be compared to the baseline of when the human is not wearing, controlling, or affected by the robot. Therefore, additional exoskeleton performance metrics suggested by the authors include the following:

- Duration: maximum time that a task can be performed with the use of an exoskeleton as compared to the task being performed without the exoskeleton
- Speed: velocities that can be achieved and sustained with the use of an exoskeleton as compared to the task being performed without the exoskeleton
- Acceleration/Deceleration: accelerations/decelerations that can be achieved with the use of an exoskeleton, as well as expected rapid movement impeded by the exoskeleton, as compared to the task being performed without the exoskeleton
- Pose Uncertainty: accuracy/resolution (e.g., precision to move to a commanded location and orientation) and repeatability (e.g., move to the same commanded location more than once) for the exoskeleton 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 components of the exoskeleton when they are both driven or not driven.
- Vertical Maneuvering *(see Navigation above)*: capability, speed (for lower body exoskeletons) to traverse inclines, steps, undulating terrain and (for upper body exoskeletons) to lift loads
- Horizontal Maneuvering *(see Navigation above)*: capability, speed (for lower body exoskeletons) to move the body or torso forward, back, side-to-side and (for upper body exoskeletons) to move the arm(s) forward, back, side-to-side
- Ergonomics: measure of comfort (pain, fatigue) and posture of the body when wearing an exoskeleton
- Ingress/Egress Complexity: difficulty in putting on or taking off the exoskeleton
- Ease of use: simplicity of initial training and ease of control of the exoskeleton as it allows or improves task completion performance
- Other: cost, portability, battery life, range of use, environmental, cyber security

Complications arise when ergonomics are included since comfort and posture are not typical metrics considered in industrial or response robotics. Combining ergonomics with, for example, duration, speed, etc. provides limitations to these metrics. One such example may be that task duration and speed are increased when using an exoskeleton until a period of time or a maximum speed is reached where the body starts to feel pain or other discomfort due to muscle fatigue. In [7], tests using exoskeletons for welding and painting were "continued until the quality reached an unacceptable level" during operator fatigue measurements. Tests were stopped when: the subject felt too much pain, the quality-of-work score dropped below a threshold, the subject used other parts of his/her body to continue the task, or the examiner felt that the subject was at a safety risk. In the last "other" category, a list of miscellaneous metrics is provided that may affect the potential user's decision whether to procure exoskeletons and/or how well a subject wearing an exoskeleton can perform tasks.

Additional measurements that are not explicitly discussed here, but that can be conducted in conjunction with the proposed tests include clinical measures of walking performance [8] and other measures of human performance, such as might be used in the rehabilitation community. Furthermore, there are measures of vitals, including heart rate, blood pressure, oxygen demand, etc. [9] that should also be considered.

3. Standards

Safety standards for exoskeletons are well underway and are briefly described in the chapter on regulations for medical and non-medical exoskeletons. However, performance standards for exoskeletons have not started to be formulated in a coordinated manner. Beyond the current standards section is a section on cross-industry performance standards with sub-sections listing industrial robot and response robot performance standards efforts and publications. These efforts may also provide guidance for future developments of exoskeleton standards.

3.1. Safety Standards

ISO 13482:2014 [3] safety requirements for personal care robots covers safety protocols for three robot types: mobile servant, person carrier, and physical assistant. Exoskeletons are described as physical assistant robots and their safety risk assessment and mitigation procedures are described. Figure 1 shows the basic assistive device designs from 13482 Appendix D. The classes of physical assistant robots show only example designs of what is an exoskeleton and not how well, how long, or how safely they can perform. The functional tasks for each assistive exoskeleton designs are:

- *Leg motion assistive exoskeleton*: Applying cooperative control to a user's thighs in order to control the stride and to achieve comfortable walking.
- *Body weight supportive exoskeleton*: Reducing the load on legs, hips, knees, and ankles while standing or walking by supporting part of or fully the user's bodyweight.
- *Exoskeleton wearable robot*: Physically supporting a human and manipulating body parts through direct interaction and fixtures to the person, e.g., via straps or clamps. Enabling the user to carry loads similar to or above average human strength.

Exoskeletons provide assistance to the user as perhaps described in these three designs. The body weight supportive device is, however, similar to a motor bike where the user "rides" on the exoskeleton system and this is therefore not considered wearable. The leg motion assistive exoskeleton design allows it to rest on the user, potentially without straps or other means of attachment. Therefore, only the exoskeleton wearable robot is attached to the body and is the physical assistant robot design addressed in this chapter.

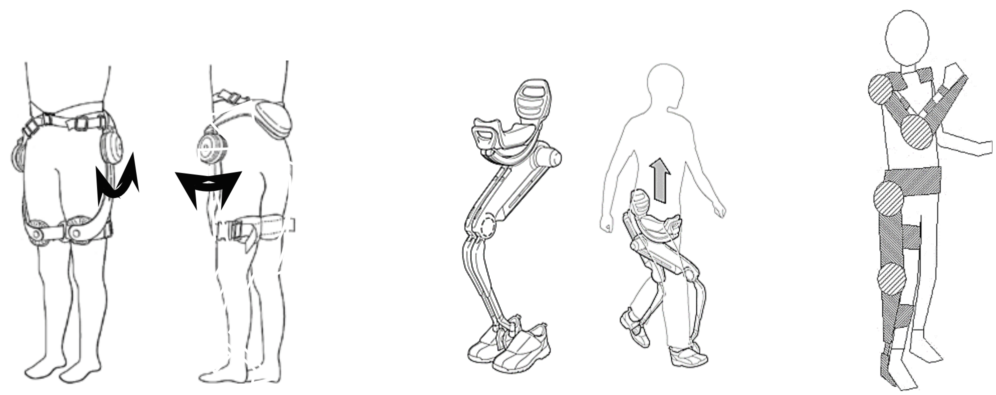

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Figure 1 - Basic exoskeleton designs shown in ISO 13482 Appendix D: (a) Leg motion assistive device, (b) Body weight supportive device, (c) Exoskeleton wearable robot.

Experts from China, France, Germany, Japan, Korea, United Kingdom, USA, and other countries are developing a standard for exoskeleton robots to provide test methods for ISO 13482 within ISO Technical Committee 299, Working Group two (WG2) [10]. The current ISO/Committee Draft (CD) Technical Report (TR) 23482-1 Robotics - Application of ISO 13482 - Part 1: Safety-related test methods [11] draft covers physical hazard characteristics for "wearable robots", stress for skin, principle, apparatus, and procedures sections. The principle "stress for skin" test method describes three steps that utilize simulation and a test dummy to define, test, and record contact states and maximum load on the human body at the location where the wearable robot is worn. A "wearable robot cuff" is described in the apparatus and the procedure involves attaching the cuff to a dummy having artificial skin. A three-dimensional (3D) load device moves the cuff for the length of load time specified. The load device generates load patterns specified where "the pattern of maximum load on the human body skin simulation device is measured during the operation". The load measurements are then recorded with the data logging process also described in the standard.

Additionally, the draft standard provides a test method that "inspects visible damage (e.g., fracture, deformation, or disengagement of parts) and functional damage (e.g., abnormality of control system) of a robot from continuous locomotion in order to estimate durability throughout its design life". The test covers robots worn by a person to provide walking assistance where the device may harm the wearer. The test includes set-up, test motion, and inspection as well as test support surface (simulation, e.g., treadmill, of the intended robot-worn or robot-use environment), test dummy, and supporting device apparatus as needed for the test. The test method also includes accelerated testing (e.g., increased speed of the treadmill).

As mentioned in section 1, there currently are no exoskeleton performance standards. As a potential crossover from other standards, we provide in this section a list of current and developing industrial and response robot performance standards.

3.2. Cross-Industry Performance Standards

3.2.1. Industrial robots

Performance standards are currently being developed for driverless automatic guided industrial vehicles (i.e., ASTM F45 [12]) and are already published for industrial robots (i.e., ISO 9283 [13]). The industrial robot performance standard ISO 9283 provides methods for measuring performance of robot arms. ASTM F45 includes five subcommittees developing the following documents for any type of industrial vehicle, generically termed "automatic/automated/autonomous-unmanned ground vehicles (A-UGVs)":

- F45.01 WK54576 - Standard Practice for Recording Environmental Effects
- F45.02 WK48955 - Standard Test Method for Navigation: Defined Spaces for A-UGVs
- F45.03 WK54662 - Standard Test Method for Grid-Video Test Method for A-UGVs
- F45.04 WK54431 - Standard Practice for Communication and Integration Interruptions for A-UGVs
- F45.91 ASTM F3200-16 - Standard Terminology for Automatic Guided Industrial Vehicles

Documents designated by "WK" are working drafts, whereas "ASTM" denotes an approved standard. WK48955 discusses test methods with physical and virtual barriers defining test spaces for A-UGVs to navigate within. Test spaces are intersection or "L-shaped" with curved or chamfered corner designs to test industrial vehicles. WK54576 can be applied to any test method, e.g., WK48955, providing a consistent and practical recording method to describe the environment during the test. A similar navigation test method with varying environmental conditions can be developed and used to test humans wearing exoskeletons. The number of repetitions is outlined in WK48955 to provide a statistical confidence level for the user. As the exoskeleton may affect the wearer during a variety of human motions such as walking, running, crawling, sit-to-stand, or vice versa transfers, etc., the test should be completed with the subject initially not wearing the exoskeleton as a baseline, then wearing it while completing the test method, and repeated where timing or other metric is used to measure and record performance.

WK54576 provides example recording of lighting, external sensor emission, temperature, ground surface, air quality, humidity, and electrical interference. Similarly, WK54431 provides a practice for recording types and locations of interruptions in communication when A-UGVs are deployed, either indoors or outdoors depending on their applications. Exoskeleton communication with external devices or with body measurement sensors could be similarly tested and recorded.

F3200-16 defines terminology that is useful for F45 test method development and implementation. A similar type of document would be useful for exoskeleton manufacturers, users, and test method developers to ensure consistent and unambiguous definitions of terms.

As outlined in ISO 9283, a series of industrial robot methods are described for specifying and testing performance characteristics, including: pose, distance and path accuracy and repeatability; position stabilization, overshoot, and drift; deviations; pose timing; compliance; and weaving deviations. All of these characteristics are potentially useful when measuring performance of the human-worn exoskeleton.

3.2.2. Response robots

Several performance standards have been created through the ASTM International E54 Committee for Homeland Security Applications. [14] Specifically, the E54.09 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. [15] 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 that may also apply to exoskeletons:

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)
- Mud (WK54403)

Human-Systems Interaction:

- Maneuvering, Sustained Speed (ASTM E2829)[2]
- 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:

- Localization and Mapping: Hallway Labyrinths with Complex Terrain, (planned)
- Localization and Mapping: Wall Mazes with Complex Terrain, Sparse Feature Environments (planned)

Manipulation:

[2] 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.

- Door Opening and Traversal Through Door (WK27852)
- Heavy Lifting: Grasp, Lift, and Place (WK44323)
- Extract (WK54274)
- Touch or Aim (WK54272)
- Place Object (WK54283)
- Inspect (WK54271)
- Dexterous Extract (planned)

4. Cross-Industry Measurements Applicable to Exoskeletons

4.1. Joint Rotation Axis Location

4.1.1. Background

Exoskeletons normally provide torque assistance at human joints through passive (e.g., springs, counterweights) and/or active (e.g., electrically-powered) mechanisms. As humans vary broadly in size and shape, adapting exoskeletons to them is complex, creating a challenge to manufacturers and users to properly fit these machines to the wearer. Without proper fit, exoskeletons can produce potentially uncomfortable and/or worse, unsafe use systems for the wearers. For example, [16] describes the sizing restrictions and the sizing process and a check-list for the exoskeleton fit to the user. If the user feels discomfort, the user is to make adjustments, although there are no specifics provided on exactly how much to adjust for safe use. The goal, for example, for good fitting at the knee is to have the axis of rotation for the exoskeleton's knee remain co-located with the axis of rotation of the wearer's knee which is known to move with knee rotation (see Figure 2d).

A goniometer device has been used to measure joint rotation axis location since the early 1900s. The location of the axes highly depends on the alignment of the device to the limb. In [17], the researchers suggest that accuracy error can be up to 10°. They also suggest that through the use of a camera positioned approximately perpendicular to the leg, errors can be approximately 3° or less. Therefore, new technology can provide improvements to joint measurement.

Additionally, once properly fitted, the exoskeleton must not change position, for example by sliding down the limb due to human motion or gravity. Assuming the machine is truly fixed to the wearer, ideally, it is known exactly where human joint axes (i.e., shoulder, elbow, hip, knee, ankle, etc.) are located, where even on a single human there may be variability between right and left joint location, rotation, etc. Figure 2 (a) shows an image of a human body reference frame [18], useful for further joint angle discussion. An example elbow flexion/extension shown in Figure 2 (b) [19] shows a single axis rotation of 140°. Normal maximum elbow, hip, knee, and shoulder rotations are described in [20] as:

- Elbow: Flexion: 150°, Extension: 180°, Supination: 90°, and Pronation: 90°
- Hip: Flexion: 110° to 130°, Extension: 30°, Abduction: 45° to 50°, Adduction: 20° to 30°, Internal rotation: 40°, External rotation: 45°
- Knee: Flexion: 130°, Extension: 15°, Internal rotation: 10°
- Shoulder: Abduction: 180°; Adduction: 45°; Horizontal Extension: 45°; Horizontal Flexion: 130°; Vertical extension: 60°; Vertical flexion: 180°

A slight complication to the sagittal plane rotation is that the elbow or synovial hinge joint angle moves along the frontal plane between the humerus (upper arm) and the ulna/radius (lower arm) bones as shown in Figure 2 (c) [21]. This occurs when extended during what is referred to as the normal carrying angle. Further, in many joints, such as the knee shown in Figure 2 (d) [22], multiple joint axes occur as the knee rolls about a non-circular surface which also provides lift and also causes leg-length increase, both in the sagittal plane. The shoulder and ankle are capable of more spherical rotation motions which must also be considered for exoskeleton adaptability to humans.

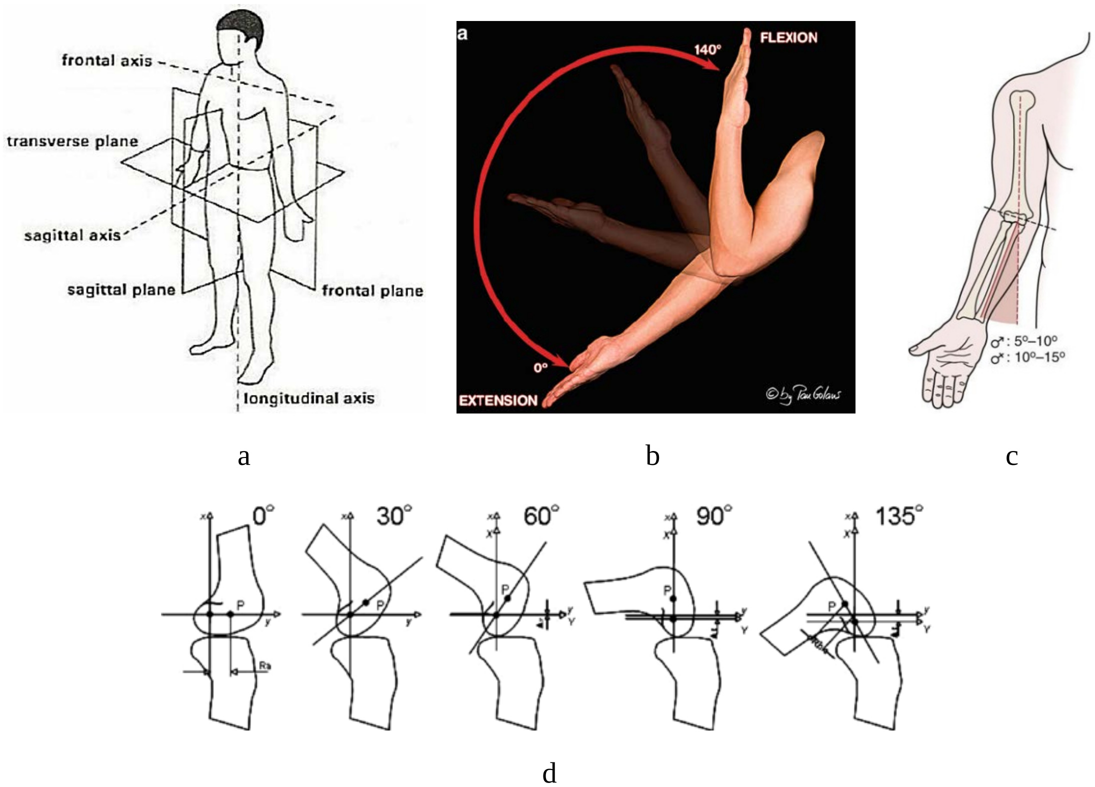

Figure 2 – (a) Human body reference planes. [18] (b) Elbow extension through flexion angle. [19] (c) Side-to-side joint rotation between the humerus and the ulna during normal carrying angle. [21] (d) Compounded knee rotation and lift at various joint angles. [22]

4.1.2. Literature Survey of Human Body Measurement

Researchers have attempted various techniques to identify the joint rotation axis location considering the simple measurement case of a human hinge joint motion. Deland et al. [23] used flashing lights captured on photographic film to measure joint rotation axis location (see Figure 3 (a)) on five cadaver arms. Bottlang et al. [24] used electromagnetic motion-tracking with radiography of an inserted screw at the estimated joint of seven cadaver arms. More recent measurement techniques use optical tracking to mainly measure human body motion. Examples of marker locations are the Plug-in-Gait, Helen Hayes (Davis), and Body Segment CM marker placement techniques [25]. Plug-in-Gait places markers only in the frontal plane. Helen Hayes (Davis) adds a marker on, for example, the upper foot and heel. Body Segment CM places a marker on each body segment. Various tests have used these and other marker placements measured by optical tracking systems to measure motion [26], bone bending [27], or to compare rigid marker sets to point clusters (see Figure 3 (b)) [28] [29] to estimate anatomical landmarks based on markers attached to a segment. The rigid marker sets are meant to limit measurement errors due to muscle and skin motion [30], although when using many markers as shown in Figure 3 (b), errors were minimized. However, positioning the markers and keeping the markers attached to the human provide challenges. Rosenhahn et al. [31] compared using markers to markerless motion capture resulting in root mean square errors of less than 3° between methods. Zhang et al. [32] used a hybrid of both marker and markerless video capture to measure body motion. Additionally, Bakhshi [33] used a marker tracking system as ground truth for comparing to an inertial measurement unit (IMU) to measure human joint angles where IMU average errors ranged from 0.08° to 3.06° for a variety of body motions. And even further, long-term joint motion was considered by [34] using electrodes sown within spandex fabric and worn by a human in motion.

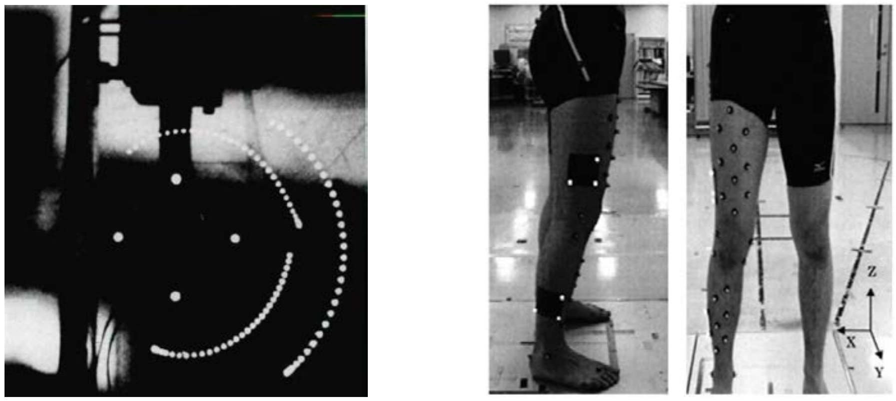

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Figure 3 – (a) Elbow rotation measurement using flashing lights captured by a camera. [23] and (b) Rigid (left) versus point cluster (right) marker sets being used to measure gait. [28]

Of key importance to all of the previous references is the notion of how certain and reliable are the measurements and the techniques used to make the measurements. For example, in the above list of normal maximum rotations from [20], it is unknown how the measurements were made and therefore, how much uncertainty there is in each measurement noting that the angles are nearly all listed in 10° increments. “Uncertainty is a measure of the 'goodness' of a result. Without such a measure, it is impossible to judge the fitness of the value as a basis for making decisions relating to health, safety, commerce or scientific excellence.” [35] The references also measure joint angles and do not describe measurement of the rotation axis location that could perhaps be derived from the angle, assuming the exact centroid axes of the links connected to the joint are known. The following subsections discuss similar techniques to the cited research although the subsections include a measure of uncertainty.

4.1.3. Robot Joint Measurement

Mori and Malik [36] considered that one might take “a single two-dimensional (2D) image containing a human figure, locate the joint positions, and use these to estimate the body configuration and pose in three-dimensional space.” Similarly, we used 2D artifacts in two experiments to measure joint rotation axis location using an industrial serial-link manipulator or robot arm and an optical tracking system (OTS). The measurements were used to consider OTS capability for measuring human-worn artifacts and to consider two test methods using an OTS and artifacts that could enable proper fitting of exoskeletons to human joints to support exoskeleton design and testing for safe use of these systems.

Industrial serial-link manipulators can have simple motion similar to the motion of human legs or arms and much can be learned using this robot system as a simulation tool. An example drawing of these simple motions is shown in Figure 4. The drawing shows labels of the human body links and joints and the unknown joint axis rotation locations for the shoulder/hip and elbow/knee joints. For simplicity, we will continue discussion of only the arm, specifically the elbow joint. An area typically not considered in industrial or other robot applications is to externally measure robot joints rotation axes locations, as was previously shown for human limbs. Robot kinematics provide the mathematical basis to properly control robots to ensure their end-effectors or attached tools are located at expected positions and orientations in joint or world space coordinates. However, it may also be necessary to physically measure the joint rotation axis location to adapt external apparatus to the robot, such as hard-mounted devices/tools or sensor sleeves/skins, and/or to accurately know the joint rotation in the case of tight-tolerance robot accessibility to openings. Using new optical tracking system technologies and applying a concept for an alternative test method for measuring joint rotation axis locations of both robots and humans, an experiment was performed at NIST on a 1300 mm (51.2 in) long robot arm.

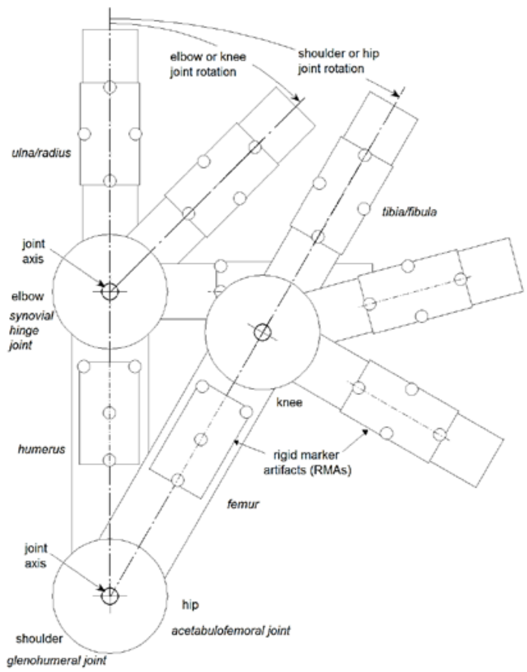

Figure 4 – Joint axis locations and rotations for a robot with human body labels on links and joints. Left side labels correspond to human arms and right side labels correspond to human legs. The center of the shoulder/hip and elbow/knee joints are marked. Note that only the rigid marker artifacts (RMAs) attached to the upper link were used in experiments described in this chapter.

Similar to [23] who used light markers and film to measure joint rotation axis location, NIST researchers used reflective, passive markers and an optical tracking system of 12 cameras [37] to track the joint rotation. And similar to both [28] and [29], rigid marker artifacts (RMA) were used. Two 89 mm x 152 mm (3.5 in x 6 in) flat aluminum RMAs, each with four markers in unique patterns, were symmetrically mounted onto two 3D printed arcs that matched the robot links radius-of-curvatures. The RMA was designed to also be considered as a potential fitting on to a human arm or leg.

Experiment I included attaching one RMA to the wrist-to-elbow link, parallel to the joint rotation, and rotating the link, similar to the arm motion shown in Figure 2a. Figure 5 (a) shows the experiment I setup. The RMA was mounted with its center at approximately 300 mm from the elbow joint center. The wrist-to-elbow link was rotated and measured at 5° and 10° increments from -120° to +90° at 22 different angles.

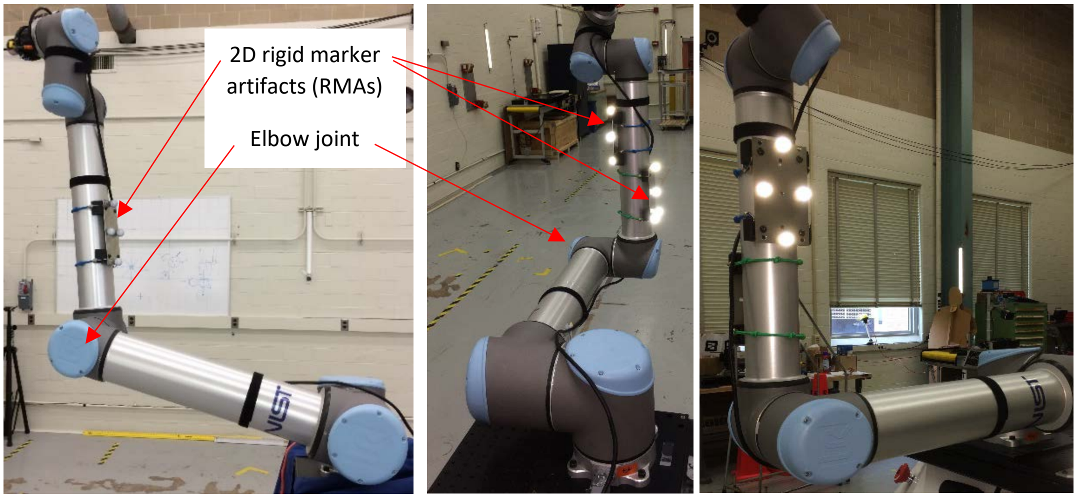

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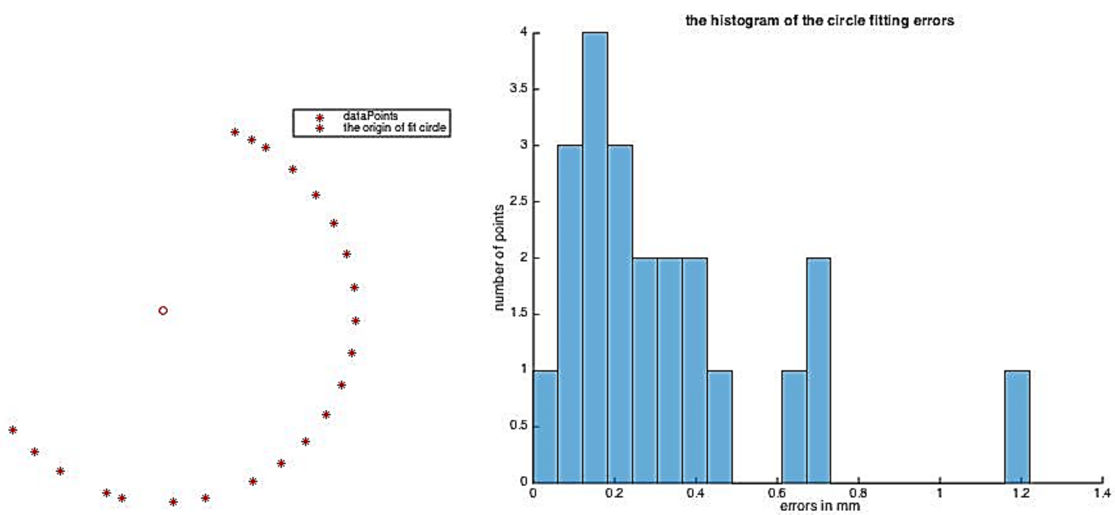
Figure 5 – (a) RMA posed on a robot arm for experiment I circle measurement method for determining elbow joint rotation axis location. (b) Shoulder-to-elbow view and (c) side view (top RMA visible, bottom RMA not visible) of illuminated (from camera flash) photos of two RMAs posed on the robot wrist-to-elbow link for experiment II for measuring uncertainty of joint rotation axis location.

4.1.4. Results

A circle was fitted to the data set and a histogram of the circle's fit error was calculated (see Figure 6). Results showed that the data provided a mean fitting error of 0.34 mm with an uncertainty of 0.27 mm, i.e., a relatively high confidence in the OTS measurement method. No specification was provided for the backlash in the robot elbow, although the amount was considered negligible as compared to measured error. Hence, based on measurement with the OTS, the actual joint rotation axis location is within this uncertainty in the 2D plane along the X and Y axes.

Assuming that a human arm was measured in the same manner, the shoulder-to-elbow link would require clamping (e.g., [23] clamped a cadaver arm) with no motion while rotating the wrist-to-elbow joint at multiple angles to get results similar to experiment I. This is difficult with a live human with soft tissue in the arm and of course, the use of a clamp to allow no shoulder-to-elbow link motion.



a b

Figure 6 – (a) Plot of data points and calculated center joint rotation location after circle fit.

(b) Histogram of experiment I data fit to a circle to find the uncertainty for the joint rotation axis location.

Ideally, a single joint angle is used to measure joint rotation axis location, especially as described in section 4.1.3, since the location changes with flexion or extension of the limbs. Therefore, in experiment II, the elbow was set to 90° using the robot controller, the two RMAs were attached parallel to one another and perpendicular to the joint rotation on the wrist-to-elbow link (see Figure 5 (b and c), and a random 11 measurements were performed using the OTS. A computer program was designed and used to analyze the data to determine the uncertainty of the joint rotation axis location measurement. Also, electronic calipers were used to measure marker center attached to the RMA and RMA (top) to RMA (bottom) distances. As per [34], the propagation of standard deviation uncertainty is calculated using:

$$\sqrt{U(EWtop)^2 + U(EWbottom)^2 + U(caliper)^2} \qquad \text{EQ[1]}$$

where:

- *U(EWtop)* = the uncertainty of fitting a plane to eleven OTS measurements of the upper RMA relative to the link center,
- *U(EWbottom)* = the uncertainty of fitting a plane to eleven OTS measurements of the bottom RMA relative to the link center, and
- *U(caliper)* = the uncertainty of five electronic caliper measurements of the {[marker center to RMA] x 2 + [RMA(top) to RMA(bottom)]}/2 = center location of the robot link. The [RMA(EWtop) to RMA(EWbottom)] measurement include two measurements on either side of the link to mathematically cancel out non-parallel RMA pose.

The resulting uncertainty for experiment II was therefore: $\sqrt{1.04^2 + 1.5^2 + 1.9^2} = 1.93$ mm or nearly seven times larger than the results of experiment I. Also, by comparison, several RMA pose concepts were tested to determine the lowest uncertainty for locating the joint rotation axis location, including:

- Perpendicular RMAs,
- One RMA on the shoulder-to-elbow link and one RMA on the wrist-to-elbow link parallel to one another, perpendicular to the joint rotation, and offset by the robot links,
- One RMA on the shoulder-to-elbow link and one RMA on the wrist-to-elbow link parallel to one another, perpendicular to the joint rotation, and aligned in the same plane using an offset mount equal to the robot links offset.

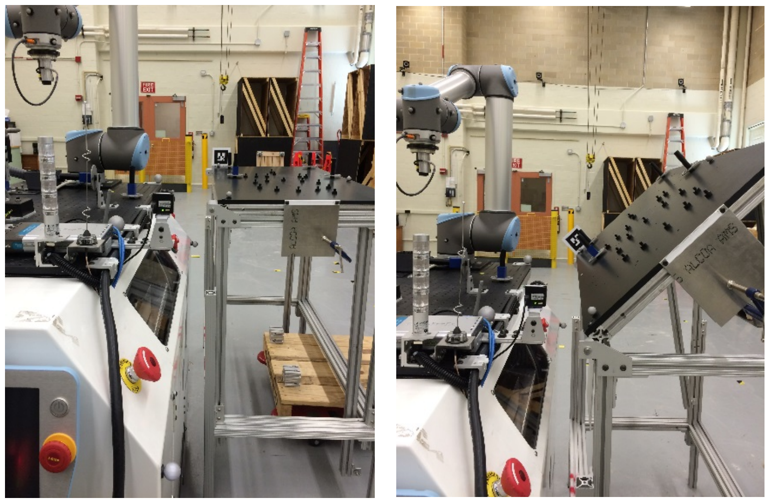
Upon analysis, none of these methods provided lower uncertainty than the parallel RMA method.

4.2. Industrial Mobile Manipulator

As discussed in section 4.1, measurement of exoskeleton performance can also utilize measurement concepts developed for industrial robots. Specifically, in this section the use of artifacts to measure mobile manipulator performance is discussed where ground truth measurement from an optical tracking system was compared to making use of an artifact [37]. Cross-industry measurements used on industrial robots are envisioned to also be useful for exoskeleton performance measurement where exoskeleton wearers would walk up to an artifact, demonstrate pose performance for performing peg-in-hole and other tests.

Measurement science for smart manufacturing robotics is being researched at NIST. [4] As part of this research, simple, cost-effective, repeatable performance measurement methods are being developed and tested and applied towards developing potentially new performance standards for mobile manipulators (i.e., robot arms onboard mobile robot bases). [38][39][40]

Figure 7 shows examples of the mobile manipulator moving towards an artifact, called the reconfigurable mobile manipulator artifact (RMMA-1). In Figure 7 (a), the RMMA-1 is horizontal while in Figure 7 (b), it is angled at 45°. The reconfigurability of the artifact allows it to provide the means to measure manipulator alignment of a laser carried by the manipulator with 1 mm diameter or larger reflectors positioned in simple-through-complex geometric patterns on the RMMA-1. Without making contact, the mobile manipulator can be measured to a known artifact when posed at an infinite number of vehicle orientations. Future mobile manipulator measurements will utilize the RMMA-2 shown in Figure 7 (c) and (d). This artifact will allow measurement of a dynamic mobile base as well as manipulator performance. Both RMMAs are also potentially useful models of how human-worn exoskeleton performance can be measured.



a b

c d

Figure 7 – (a) Automatic guided vehicle with onboard robot arm moving to dock with the NIST reconfigurable mobile manipulator artifact (RMMA-1) angled (a) horizontal and (b) at 45°. RMMA-2 computer aided design models angle in the (c) vertical and (d) horizontal configurations.

4.3. Response Robots

As with industrial robot performance measurement, response robot performance is also being measured and standard test methods are being developed for these robots. [41] These test methods are expected 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 on inclined planes, steps, undulating floors or more complex or unstructured terrains, and around obstacles as illustrated in Figure 8. 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), 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 normally required.

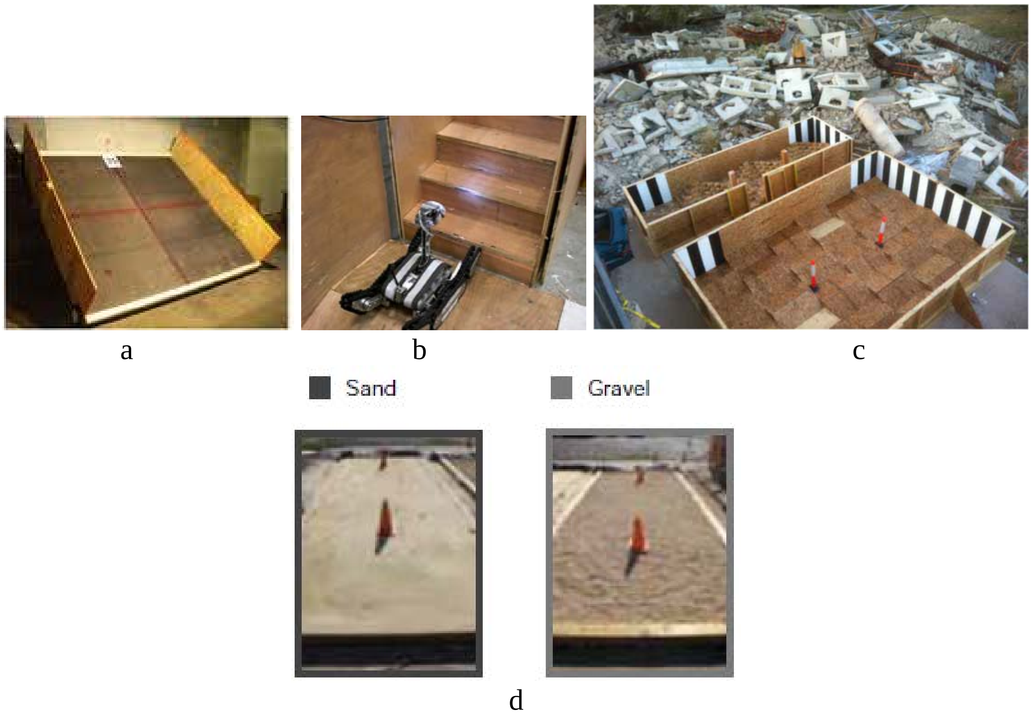


Figure 8 - Examples of (a) inclined planes, (b) stairs, and (c) varying terrain test apparatus and actual varying terrain (above the apparatus). (d) Example artifacts of sand and gravel terrains.

5. Recommended Test Methods for Exoskeletons

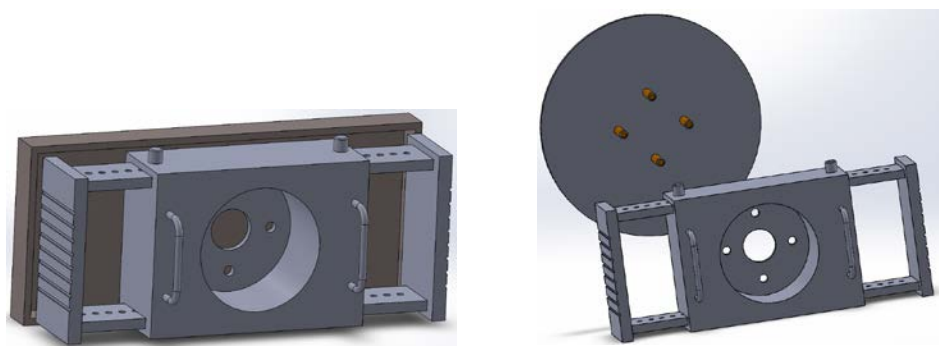
Safety and performance measurements of exoskeletons can be intertwined; for example, how safe is the system to the wearer after walking, changing direction, stepping on soft versus hard surfaces, etc. As described in section 2, there are many metrics to consider when describing the effects of exoskeletons, both on the human body and on how well the exoskeleton can help humans perform the wide variety of motion tasks. Repeatable test methods can help exoskeleton manufacturers and users highlight capabilities of their systems, compare these exoskeletons to their motion tasks, show design flaws or enhancements, and help with procurement requirements. Ideally, these test methods are not only repeatable, but also standardized, as with the International Organization of Standards (ISO) Technical Report (TR) 23482-1 being developed, such that both manufacturers and users can simply select a document that describes how to perform the test method no matter which exoskeleton they make or use. Sections 3 and 4 described test methods for other industries that can cross the industry boundary to also apply to exoskeletons. As a direct application to exoskeletons, we recommend in this section the performance measurement concepts that should be considered for development of performance test methods for exoskeletons. Variability in generic loads, positioning heights, defined motion spaces, etc. can also be detailed in follow-on research and standards from these recommended test methods to help exoskeleton designers fit the tasks to the potentially wide variety of exoskeleton wearers.

5.1. Load Handling

A docking test apparatus can be used to measure a variety of exoskeleton-worn tasks, such as: load carry, position, and orient; peg-in-hole insertion; and tooling forces. Figures 9 and 10 show computer-aided design (CAD) models, developed by the authors, of the load-handling device and docking test apparatus concepts pictorially, respectively, and the tasks are explained in the following sub-sections.

5.1.1. Load Carry, Position, and Orient

Exoskeletons are being developed to not only support the human but to also allow load handling equal to and above normal human load carrying capacity. Loads can dramatically vary dependent upon the application. However, load handling includes not only picking up but also placing loads, sometimes with relative precision (e.g., installing a wheel on a vehicle axle bolt circle). Ideally, a single, replicable artifact is used for docking tests. Figure 9 shows a concept for a generic artifact with variable width measuring from approximately 500 mm to 1200 mm wide called the Adjustable Payload Artifact (APA) that can be used to measure, using pass/fail scoring criteria, how well the exoskeleton wearer can place, in both position and orientation (pose) the APA.



a b

Figure 9 –APA shown with (a) docking pose tray, and (b) docking bolt pattern.

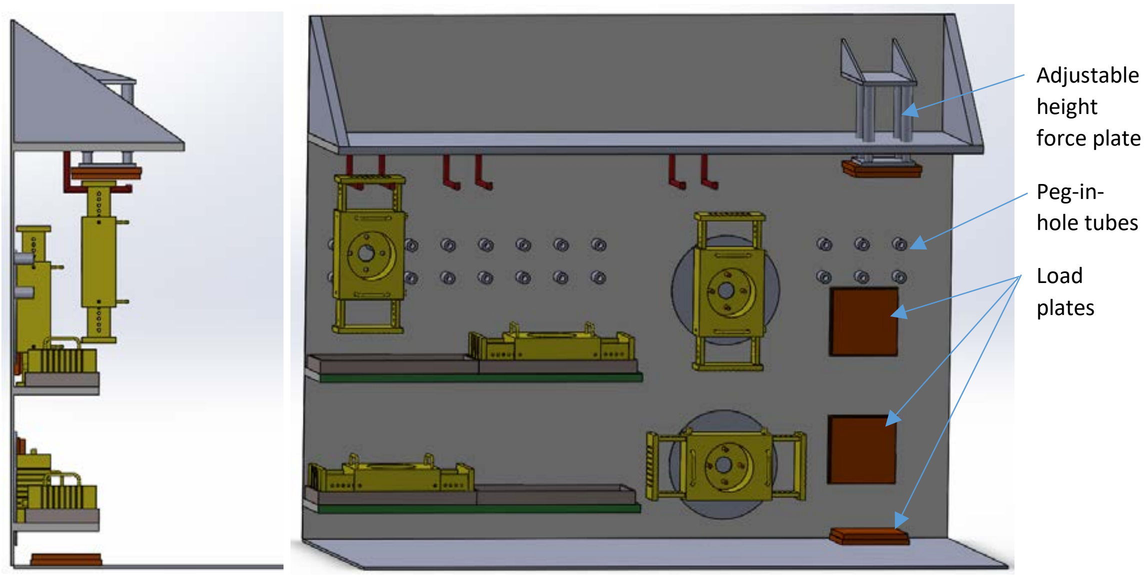
Different types of load grasping can be achieved with the APA, including: handles (e.g., equipment), knurled ends (e.g., vehicle tires), and underneath with both arms (e.g., boxes). The APA can be placed in a rectangular tray(s) of variable sizes (see Figure 9 (a)), with chosen tolerance where simultaneous alignment of APA edges and corners to the tray are required. Similarly, as with the task of installing a wheel on an axle bolt circle, the APA includes a hole pattern (see Figure 9 (b)) to mate to a bolt pattern mounted, for example, on a wall or frame.

5.1.2. Peg-in-hole

The docking test apparatus in Figure 10 measures ≈3600 mm wide x 3000 mm high x 1200 mm deep and shows tubes mounted to the back wall for peg-in-hole testing. Similar to the industrial mobile manipulator testing with the RMMA (see section 4.3), the subject wearing an exoskeleton could maneuver simple pegs or a tool, such as a drill, with drill bit to insert into the tubes as an additional position and orientation test. Ideally, the load handling and peg-in-hole tests require that the exoskeleton wearer stands in one location or must move to other locations to position and orient the APA, pegs, or tools to match tray, hook, or tube locations as part of the test method.

5.1.3. Tool Force

The docking test apparatus shows force plates mounted on the floor, wall, and an adjustable height (and perhaps angle) ceiling mount (see Figure 10). As tools, such as grinders, saws, drills, etc., are potentially used by exoskeleton users, test methods are needed that measure the user without wearing the exoskeleton as baseline and wearing the exoskeleton to compare performance. The user can walk up to the force plates with tools, apply the tool to the force plates for a test period of time, and measure force applied to user-fatigue time periods. Applied force versus time at a number of heights can be measured with this concept.

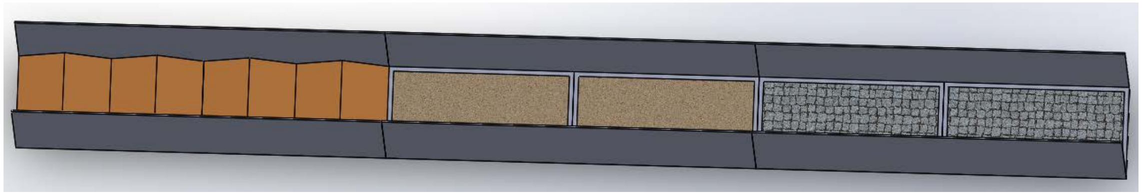


a b

Figure 10 shows (a) the side view and (b) the front view of a test apparatus with the APA trays and bolt patterns, as well as holes for peg-in-hole insertion, hooks for hanging the load, and load plates for applying tool control forces. Pass/fail position and orient and elapsed time could be measured for multiple repetitions.

5.1.4. **Navigation**

The exoskeleton user can navigate along many different paths and subject orientations to test the safety and performance of the exoskeleton. Again, ideally, a small set of artifacts or test apparatus are used in test methods to measure safety and performance for relatively simple reproducibility. ASTM F45 is developing a navigation test method and an environmental effects practice and ASTM E54.09 combines navigation and environmental effects into methods that can also apply to exoskeletons. Figure 11 shows an example of several F45.02 navigation-straight aisle sections that also include various (undulating, sand, and stone) terrains within the sections. An exoskeleton user can test balance and timing to traverse this type of course. Touching the walls could be considered a failed navigation test and passing considered when no contact is made throughout the entire test course. Tape switches mounted to the walls or cameras can monitor wall contact. Alternatively, virtual barriers such as laser lines as described in ASTM F45.02 WK48955 could be used instead of physical barriers to detect when the exoskeleton user crosses the barrier.



a b c

Figure 11 - Example exoskeleton test method using F45.02 WK48955 navigation-straight aisle sections defined space navigation test methods with example response robot terrain types, i.e., (a) undulating, (b) sand, and (c) stone, in pans within sections.

Similarly, F45.02 WK48955 navigation-perpendicular aisle and constant radius curve sections, defined space, navigation test methods can be assembled to produce a more complex navigation performance test apparatus. The apparatus may or may not include various terrains as shown in Figure 11. The same wall contact or virtual barrier measurement and test pass/fail due to no contact/contact or barrier-cross as described above can be used. Additionally, in Figure 12, the docking test apparatus is shown at each end of the constant radius curve sections as a docking area for the subject wearing an exoskeleton. Combined navigation and docking test methods can be useful for testing load carrying through a complex maze and terrain, followed by accurate positioning of the load. Further, defined-space sections can be thought of as building blocks to assemble even longer or more complex navigation defined-space apparatus.

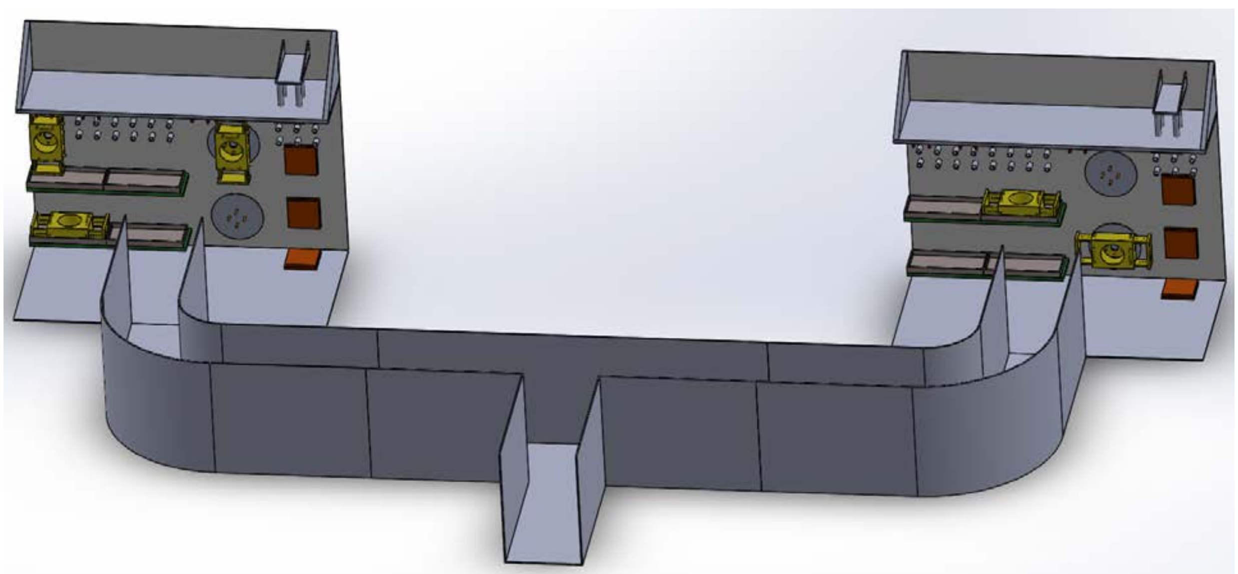


Figure 12 - Example exoskeleton test method using F45.02 WK48955 navigation-perpendicular aisle section (center) and constant radius curve sections (left and right) defined space navigation test methods leading to docking tests.

5.1.5. **Test Dummy**

Test dummies can be useful for testing mean time-between-failure of exoskeletons, skin effects, effects of off-axis joint rotation, and other areas where fatigue or unsafe conditions may be evident for human-in-the-loop tests. Hip with torso and/or single or dual: ankle, knee, shoulder, or elbow joint test dummies, along with their links, can be useful for these measurements. As described in section 4.1., Robot Joint Axis Location Measurement, the concept for measuring joint axis rotation location combined with a test dummy could provide useful information about exoskeleton fit with off rotation-axis and on rotation-axis force effects on the user prior to exoskeletons worn by humans. The development of robots with inline joints, such as humanoid robots, could be useful, so long as they directly mimic sizes and motions of the variety of humans who intend to use exoskeletons.

Figure 13 shows a CAD model, developed by the authors, of a modular upper body test dummy for testing exoskeletons. The arms and shoulders are actuated similar to human biomechanical motions, as shown by the opening in the arm at the elbow joints. A similar modular lower body can also be added or independently used. The joints are in-line with the actuators inside the hollow shell. The dummy is modular, potentially even 3D printed components, so that components with smaller or larger shoulder span, arm length and diameter, torso diameter and more human-like shapes, etc. can be modified and refastened to the overall frame to test a certain size/shaped person. The torso can be divided into further segments to allow for torso twist between the shoulders and hips. Padding, that can mimic human flesh and able to change shape, can be added to the modular components as desired. Similarly, sensors to measure exoskeleton effects and electrical and magnetic activity to output to exoskeleton components that use electrocardiography or electromyography [42] for exoskeleton control can also be added as needed. Since the test dummy control can be simple or complex, a system's engineering approach can also be applied through concepts such as systems modeling language (SysML) [43]. Joint(s) actuation, sensing, and combined system motions, including feedback from the exoskeleton can all be integrated into a model and potentially controlled using SysML.

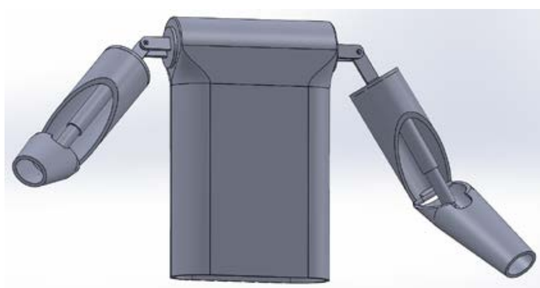


Figure 13 – Modular human upper body test dummy for testing exoskeletons

Ideally, a passive measurement-exoskeleton strapped to a range of humans representing various sizes, shapes, fitness-levels, and both genders can measure actual human motion with data for replication in test dummies to mimic human biomechanical motions when testing exoskeletons. Sensors integrated within the test dummy, like those used on the passive measurement-exoskeletons, can also measure chafing, device movement, torques and other forces, etc. to provide additional information. Eventually, two or more test dummy joints, such as ankle and knee, ankle and knee and hip, etc., joints with adjustable links can be combined into more complex test dummies for repeatable and improved measurements of exoskeleton effects on humans. These concepts may also provide useful short- and long-term effects measurements on humans and on exoskeletons to improve wearable exoskeleton designs to be safe and increase performance.

6. Summary and Conclusions

Much can be learned from the industrial robot and response robot sectors that can be used to support safety and performance measurements of exoskeletons prior to or when they are used by humans. This chapter builds on referenced human-robot interaction metrics that may apply to exoskeletons to include typical industrial robot metrics of speed, pose uncertainty, control force, etc. Additionally, more human-related metrics of ergonomics, ease-of-use, ingress/egress complexity, etc. are added and defined by the authors that more relevantly apply to exoskeletons. The ISO 13482 safety standard for physical assistant robots directly addresses exoskeletons. However, only recently the ISO TR 23482-1 technical report is under development to support the safety requirements standard with how appropriate test methods can be developed. There are currently no test methods for safety and performance measurements of exoskeletons and lessons can be learned from recent industrial performance standards developments under ASTM F45 and response robot performance standards developments under E54.09. Many of these standards and working documents were listed in this chapter.

To aid in exoskeleton design, development, and use was a discussion on cross-sector measurements that also include experiences from industrial robot and response robot domains. Joint rotation axis location can dramatically vary from joint-to-joint and from person-to-person. Additionally, limitations, joint motion, and over-extension caused by exoskeletons must be addressed before humans can safely use them. For example, an exoskeleton moving an upper and lower leg about the knee must move as the human knee moves. Additionally, the location of the limb-mover must be aligned properly with the human joint and known angles of motion must not be exceeded. Relatively old goniometer technology and referenced measurement concepts may suffice for exoskeleton joint positioning should the uncertainty be known, although minimal uncertainty information for joint location has been published. NIST performed experiments with rigid marker apparatus using an industrial robot arm to determine uncertainty when using a state-of-the-art optical tracking system. The results for two concepts are 0.27 mm and 1.93 mm. Hence, potentially minimal unsafe torque would be applied to the human joint from an exoskeleton that was positioned with these offsets from the actual joint axis should today's optical tracking systems be used in conjunction with the exoskeleton being fit to the human.

Further, tests using mobile manipulator and response robot artifacts can provide relatively low-cost environments and methods for measuring performances of these systems. A direct cross-over can be applied to exoskeletons as provided in the recommended concepts in this chapter. Load handling, navigation, and perhaps other test concepts can be made into generic methods for testing system performance. Test dummies are another pre- or parallel test method for performance measurement of exoskeletons to test mean-time-between-failure, how failures can occur, etc. without having people in the wearable robot in potentially unsafe conditions. Test dummies and computer models can be designed to match human physique, speed, joint motion characteristics, sensing, control, and many other biomechanical parameters to fully understand the exoskeleton effects on humans. Future efforts should include developing some or all of the recommended concepts suggested to develop the safest, highest performance, and most cost-effective exoskeletons to support or enhance human activities.

7. Acknowledgements

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