Preliminary Development of Test Methods to Evaluate Lower Body Wearable Robots for Human Performance Augmentation

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Overview

- Prevalence of wearable robotics in multiple domains
  - **Medical**: Rehabilitation and/or prosthesis of disabled persons

ReWalk Robotics 6.0
Photo from [http://rewalk.com/](http://rewalk.com/)

Ekso GT
Photo from [http://eksobionics.com/](http://eksobionics.com/)

Keeogo
Photo from [http://keeogo.com/](http://keeogo.com/)
Overview

- Prevalence of wearable robotics in multiple domains
  - Industrial/Military: Performance augmentation of able-bodied persons

Ekso Works
Photo from http://eksobionics.com/

DARPA Warrior Web
Photo from http://army.mil/

B-Temia
Photo from http://b-temia.com/
Overview

• Few common metrics and evaluation methods
  – Biometrics like metabolic cost most prominently, but is incomplete
  – Subjective surveys

• Human Augmentation Roundtable held December 2014
  – Test methods for performance and safety are needed to compare systems to aid industry growth, procurements, standards, etc.

• Baseline set of tasks has been developed to be used as basis for test method development
  – Test method drafts in progress, currently validating
Related Test Method Suites

• ASTM E54.08.01 Homeland Security Applications; Operational Equipment; Robots

• ASTM F45 Driverless Automatic Guided Industrial Vehicles

• Both committees develop test methods largely reliant on directly observable performance in physical apparatuses that represent abstract versions of tasks to exercise robotic capabilities such as mobility, manipulation, navigation, and obstacle avoidance
Related Test Method Suites

• Marine Corps Load Effects Assessment Program (MC-LEAP)

• Physical tasks performed in an obstacle course to measure the impact of worn or carried items on a soldier

Photo from http://humansys.com/
Approach – Existing Research

• Many publications regarding development of wearable robotic systems or exoskeletons, generally measuring metabolic cost
  – Oxygen consumption, heart rate, electromyography
• Repetitive motions specific to body part that device is meant to actuate/assist, or walking on a treadmill
• Control with no device, trial with device (powered vs. unpowered)
• Separate practice and test sessions to avoid fatigue
Approach – Test Method Design

- Test apparatus physical design dictates performance metrics and provide discernible scoring measurements

- Task-based metrics for holistic testing, abstracted to be broadly applicable and platform agnostic

- Fabricate test methods using readily available and inexpensive materials
Approach – Considerations

• Focusing on performance augmentation, meaning the user is an able bodied person and is be able to perform the task in some capacity without the system

• Tasks being performed should elicit extra work from the user for the system to assist, augment, offset, etc.

• Actively powered exoskeletons predict and/or react to movements from the user

• Stationary performance spaces (e.g., treadmills) can limit the tasks that can be tested, and some systems require physical movement through space rather than just local joint movement

• Long-term effects are also possible, but beyond our scope
Test Method Development

• Categories
  – Range of motion: exercising potential restrictions in movement
  – Task performance, endurance: repetitive tasks that can be performed for shorter or longer periods of time
  – Task performance, loading: lifting, carrying, or dragging weight
  – Transitions between poses/modalities: dynamic maneuvers between perceived system modes

• Not mutually exclusive from one another, but used for initial development
Test Method Development

Range of motion

Leg Lift

Split
Test Method Development

Task performance, endurance

Squats
Lunges
Test Method Development

Task performance, loading

Lifting and Carrying

Munitions Loading
Test Method Development

Transitions between poses, modalities

Slaloms

Underpass
## Test Method Development

<table>
<thead>
<tr>
<th>Category</th>
<th>Test method name</th>
<th>Task description</th>
<th>Body part(s) exercised</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range of motion</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stairs</td>
<td>Walking up and down 35 degree stairs</td>
<td>Lower body (focus on knees)</td>
</tr>
<tr>
<td></td>
<td>Hurdle, walk over</td>
<td>Walk over 30 cm (1 ft) hurdle; left leg over first, right leg over first</td>
<td>Hips, knees</td>
</tr>
<tr>
<td></td>
<td>Hurdle, climb over</td>
<td>Walk over 61 cm (2 ft) hurdle; left leg step on with right arm support, right leg step on with left leg support</td>
<td>Hips, knees</td>
</tr>
<tr>
<td></td>
<td>Jump</td>
<td>Jumping as high as possible in a stationary position</td>
<td>Ankles, knees</td>
</tr>
<tr>
<td></td>
<td>Leg lifts</td>
<td>Lifting foot off ground as high as possible, knee bent or out straight; left leg, right leg</td>
<td>Hips, knees</td>
</tr>
<tr>
<td>Task performance, endurance</td>
<td>Walk</td>
<td>Walking for X distance</td>
<td>Full body (focus on lower body)</td>
</tr>
<tr>
<td></td>
<td>Run</td>
<td>Jogging/running for X distance</td>
<td>Full body (focus on lower body)</td>
</tr>
<tr>
<td></td>
<td>Lunges</td>
<td>Lunging X number of times</td>
<td>Hips, quads, knees</td>
</tr>
<tr>
<td></td>
<td>Squats</td>
<td>Squatting X number of times</td>
<td>Hips, quads, knees</td>
</tr>
<tr>
<td>Task performance, loading</td>
<td>Munitions storage</td>
<td>Arm-carried load moved between positions without traversal</td>
<td>Full body (focus on knees, lower back)</td>
</tr>
<tr>
<td></td>
<td>Lifting and carrying</td>
<td>Arm-carried load moved between positions after traversing through apparatus</td>
<td>Full body (focus on knees, lower back)</td>
</tr>
<tr>
<td>Transitions between poses/modalities</td>
<td>Suicides</td>
<td>Running to other end of apparatus and touching the ground</td>
<td>Lower body</td>
</tr>
<tr>
<td></td>
<td>Underpass</td>
<td>Transitioning from standing to prone to standing</td>
<td>Full body (focus on knees, hips)</td>
</tr>
<tr>
<td></td>
<td>Slaloms</td>
<td>Alternating between lateral movements while avoiding obstacles</td>
<td>Full body (focus on knees, ankles)</td>
</tr>
<tr>
<td></td>
<td>Pitched footfalls</td>
<td>Stepping on alternating pitched surfaces to direct ankle pitching forward and backward</td>
<td>Ankles, knees</td>
</tr>
<tr>
<td></td>
<td>Dynamic or compressible terrain</td>
<td>Walking on sand or gravel</td>
<td>Lower body</td>
</tr>
<tr>
<td></td>
<td>Inclined plane</td>
<td>Uphill to downhill traverse</td>
<td>Ankles, knees</td>
</tr>
</tbody>
</table>
Procedure and Metrics – Considerations

• Systems not designed for immediate use and require practice

• Variable settings on the device, both hardware and software

• Proper task performance

• Number of repetitions

• Multiple tests over time
Internal Validation

• Exercised using B-Temia system which actuates the knee
  – Dermoskeleton that straps to the user as opposed to the user “getting into” the system like traditional exoskeletons

• Performed tasks wearing 18 kg weighted vest to elicit extra work from the user; 10 repetitions each

• One control session, four test sessions (weekly); randomized task order each day

• Heart rate and informal subjective data recorded
Internal Validation

Underpass

Control --> Test 1 --> Test 4
Internal Validation

Rushes ("Suicides")

Control --> Test 1 --> Test 4
Internal Validation - Results

• Heart rate (relative to standing per day) compared to control to determine average difference

• Some tasks saw average increased heart rate suggesting the user performed more work, others decreased

• User experience not always improved with reduced heart rate

• Tasks like these expose limitations and advantages for system’s predictive/reactive behaviors to user input
## Test Method Development – Updated

<table>
<thead>
<tr>
<th>Category</th>
<th>Test Method</th>
<th>Task Description</th>
<th>Motion-to-Motion &amp; Transitions</th>
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<tr>
<td><strong>Range of Motion</strong></td>
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<td></td>
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<td>Walking up and down 35 degree stairs</td>
<td>Stationary/Forward/Ascend/Descend/Forward/Stop/Turning</td>
</tr>
<tr>
<td></td>
<td>Hurdle (walk over)</td>
<td>Walking over a 1’ or 2’ hurdle; Left leg over first, right leg over first</td>
<td>Stationary/Forward/Single Leg Lift/Forward/Stop/Turning</td>
</tr>
<tr>
<td></td>
<td>Hurdle (climb over)</td>
<td>Climb over 2’ hurdle; Left leg step on with right arm support, right leg step on with left leg support.</td>
<td>Stationary/Forward/Climbing/Forward/Stop/Turning</td>
</tr>
<tr>
<td></td>
<td>Jump</td>
<td>Vertical jump as high as possible from a stationary position.</td>
<td>Stationary/Crouch/Stand</td>
</tr>
<tr>
<td></td>
<td>Leg Lifts</td>
<td>Lifting foot off ground as high as possible, knee bent and then knee straight; left leg, right Leg</td>
<td>Stationary/Single Leg Lift/Stand</td>
</tr>
<tr>
<td></td>
<td>Forward Split</td>
<td>Split legs forward as far as possible; left leg forward, right leg forward</td>
<td>Stationary/Forward/Stationary</td>
</tr>
<tr>
<td></td>
<td>Lateral Split</td>
<td>Split legs laterally as far as possible</td>
<td>Stationary/Lateral/Stationary</td>
</tr>
<tr>
<td><strong>Task Performance (Endurance)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Walk</td>
<td>Walking for X distance</td>
<td>Stationary/Forward/Stop - (Turning)</td>
</tr>
<tr>
<td></td>
<td>Run</td>
<td>Jogging/Running for X distance</td>
<td>Stationary/Forward/Stop - (Turning)</td>
</tr>
<tr>
<td></td>
<td>Crouched Running</td>
<td>Walk/Jogging/Running for X distance in a crouched position with knees bent and back at a 30 degree angle.</td>
<td>Stationary/Crouch/Forward/Stop - (Turning)</td>
</tr>
<tr>
<td></td>
<td>Lunges</td>
<td>Lunging X number of times</td>
<td>Stationary/Forward/Kneel/Stand - (Turning)</td>
</tr>
<tr>
<td></td>
<td>Squats</td>
<td>Squatting X number of times</td>
<td>Stationary/Crouch/Stand</td>
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<td><strong>Task Performance (Loading)</strong></td>
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<tr>
<td>Lifting and Carrying</td>
<td>Arm-carried load moved between positions after traversing through apparatus.</td>
<td>Stationary/Forward/Stop/Crouch/Stand/Turn/Forward</td>
<td></td>
</tr>
<tr>
<td><strong>Task Performance (Agility)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rushes</td>
<td>Running between both ends of the apparatus and touching the ground with a hand.</td>
<td>Forward/Crouch/Stand/Turn - (Fast Transitions)</td>
<td></td>
</tr>
<tr>
<td>Underpass</td>
<td>Transitioning from standing to prone to standing to pass under an obstacle.</td>
<td>Forward/Crouch/X/Stand/Forward (X = Prone or Crawl)</td>
<td></td>
</tr>
<tr>
<td>Slaloms</td>
<td>Alternating between lateral movements while avoiding stationary objects.</td>
<td>Forward/Lateral/Forward/Turn - (Fast Transitions)</td>
<td></td>
</tr>
<tr>
<td>Pitched Footfalls</td>
<td>Stepping on alternating pitched surfaces to direct ankle pitching forward/backward.</td>
<td>Forward/Stop/Turn - (Inclined/Declined)</td>
<td></td>
</tr>
<tr>
<td>Dynamic Terrain</td>
<td>Walking on sand or gravel.</td>
<td>Forward/Stop/Turn</td>
<td></td>
</tr>
<tr>
<td>Inclined Plane</td>
<td>Uphill to downhill traverse.</td>
<td>Forward/AscendStop/Turn/Descend - (Inclined/Declined)</td>
<td></td>
</tr>
<tr>
<td>Foot Placement</td>
<td>Specific foot placement traversal of apparatus based on forward and lateral split range of motion.</td>
<td>Forward/Lateral/Stop/Turn</td>
<td></td>
</tr>
</tbody>
</table>
Discussion

• Biometric and motion sensors can be costly, but needed for validation
  – Cheap versions available (e.g., heart rate, pedometers)
  – Can be obstructed by system and further inhibit user

• More directly observable task metrics are needed
  – Test to failure not an option!

• Only performed tasks that the system could assist with
  – For instance, “Pitched footfalls” not tested because system does not
    actuate or assist the ankle

• Similar methodology can be used for wearable robots on other limbs
Future Work

• **Range of motion (ROM) and required augmented motions (RAM)** incurred larger impact than expected

• Developments to include considerations of ROM and RAM in design of test methods to size apparatuses/tasks appropriately

• **ROM variable**: change in dimensional size of test apparatus, artifact, or prop due to range of motion afforded by system

• **RAM variable**: change in procedure and/or shape of test apparatus, artifact, or prop due to required augmented motion from the system in order to assist the user
Future Work

• Perform ROM and RAM checks before each test method performance
• Tune test method accordingly
• Hurdle
  – ROM: hurdle height
  – RAM: stance area width
• Compare % difference between ROM and RAM for control vs. robot across persons
Future Work

• More visually discernible performance metrics

• Accuracy/control:
  – Environmental bump
  – Line following and stance area deviation
  – Starting/landing areas

• RAM
  – Cadence and step count (pedometer)

• Workload
  – % of time looking at system actuated limb(s)
Future Work

New “Zig-Zag” walking/jogging task with environmental bump walls
Future Work

Redesigned “Lunges” task with ROM foot placement zones
Thank You

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