Handy Gym: Upper Limb Assessment Device

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Abstract

Upper Limb (UL) impairment is a serious medical and economic challenge that is highly prevalent today. UL rehabilitation is critical in regaining lost function and improving quality of life. In current UL rehabilitation, there exist no robust quantitative metrics to guide therapy. Assessments utilized by therapists use ordinal numbers to characterize degree of UL function and are entirely based on observation. The subjectivity and the lack of sensitivity of this approach prevent therapists from delivering more effective therapy. The Handy Gym system is a proof-of-concept, low-cost, multi-functional yet simple device capable of quantifying UL impairment. This highly portable device can be operated in a variety of settings. The device provides five main functions mimicking common daily motions including pushing, pulling, rotating, and gross limb movement. The Handy Gym's portability, ease of use, and multi-functionality in providing quantitative metrics positions this device to create significant and sustainable impact in UL rehabilitation.

Background

Upper limb (UL) function is a facet of human motor control that is often taken for granted. However, it is essential for many daily tasks. Impaired UL function can result from traumatic brain injury (TBI), cerebral palsy (CP), or stroke. In the United States, at least 1.7 million individuals suffer from TBI with the average rehabilitation costs after four years totaling $196,460.[1,2] Estimates predict about 764,000 children and adults have CP. The National Stroke Association reported that 50% or 2 million patients per year surviving strokes require special care including physical therapy. Stroke is also the leading cause of disability in the US.[3] Among those who have suffered strokes and are undertaking rehabilitation therapy, the average Medicare cost per patient ranged from $52,000 to $75,000 in the first four years after insult.[4]

Need

Rehabilitation therapy is a critical component in recovery of function. Obtaining outcome measurements to assess patient improvement takes up to 20% of a therapist's time and is important for their daily practice.[5] Currently, therapists employ a variety of assessment scales that typically use subjective measures to grade function based on observation of a patient's movements.[6] The Action Research Armtest (ARAT), commonly cited in literature, requires a wooden box with objects of different types placed in front of the patient. The patient is then required to grasp, grip or pinch the various objects in the box and each item movement is graded on a four point scale. In stroke, the Fugl-Meyer is a commonly used assessment of motor function, sensation, and range of motion with grading scales of 0, 1 or 2.[7]

Despite their widespread use, there are several limitations associated with current clinical assessments, notably an inability to measure movement quality – i.e. smoothness and coordination which reflect how well the nervous system is able to produce efficient and reproducible movements. [8-12] Further, measures such as the Fugl-Meyer do not measure UL activity but rather UL limitations.[13] Additionally, many assessments do not provide explicit insight into what aspects of motor performance is impaired. This limits the development of appropriate treatments.[14] Current assessments are time consuming and may take 30 minutes to conduct, which may prevent therapists from engaging in longitudinal research to improve UL treatment.[15,16] Given the nature of these assessments and the limited information provided, there is a critical need to develop more objective methods to assess UL function and monitor change over time.[17,18]

Current Products

Current attempts to provide quantitative assessments rely on expensive and technically challenging systems, such as three-dimensional motion capture, which are not cost-effective or easily adaptable to clinical settings. For example, robotic intervention in therapy enables the recording and quantifying of patient movement.[19] While kinematic data from robotic systems may lead to novel parameters of patient mobility, these systems are used as a mode of treatment delivery and as such, there is no expectation that robot based therapy should result in better outcomes compared to traditional methods.[20,21] Virtual reality has also been introduced to aid rehabilitation therapy. However, a recent review by Fluet and Deutsch identifies questions yet to be answered, such as the lack of tactile feedback, which is important during object manipulation tasks.[22]

Figure 1: The Simulator II (BTE™)

Currently, one can find a variety of tools and equipment providing very limited quantitative metrics. The A2 model for upper limb rehabilitation equipment (Guangzhou Yikang Medical Equipment Industrial Co., Ltd.) and the E4000 Upper Limb Exerciser (Biometrics Ltd) cost $25,000 and $6,155, respectively. The Simulator II (BTE™) is another device that is six feet tall and wide and weighs 575 lbs. (Figure 1). Although daily tasks can be replicated with The Simulator II, many different attachments must be purchased.

Figure 2: Jamar Dynamometer

All these devices seek to quantify upper limb rehabilitation. However, they have a bulky profile, are expensive, or require multiple components. Simpler devices such as the Hydraulic Jamar Hand Dynamometer can be purchased for $363, which measures the grip strength of a patient (Figure 2). However, studies have found that these devices have errors up to 3% and become less reliable with use over time.[23,24] In addition, dynamometers do not capture any metric other than maximum grip strength, limiting their overall usefulness.

There exists an urgent clinical, research, and therapeutic need to generate quantitative metrics for upper limb rehabilitation therapies. Existing products are bulky, expensive, and complex. Given the limited time a therapist has to spend with the patient coupled with the rising cost of health care, existing devices and equipment are neither attractive nor ideal solutions for therapists**.** In order to address this need, the Handy Gym was developed as a portable, low-cost, multi-functional yet simple device capable of quantifying UL impairment. There is a lack of research and devices that provide quantitative data on bimanual coordination although patients have identified it as a very important function to recover.[25] Addressing this specific deficiency, the Handy Gym can provide quantitative data for patient's bimanual coordination. Utilizing load sensors complemented with powerful software, the Handy Gym can deliver data that is more sensitive the existing assessment methods. This can improve treatment efficacy and rehabilitation therapies.[26]

Design

The Handy Gym system is an assessment tool that measures and displays important quantitative metrics associated with daily tasks. The Handy Gym is made up of three main parts: the bottle, graphical user interface (GUI), and mat (Figure 3). The three components work together to provide five major functions that resemble daily activities: push/pull, grip, twist, bottle movement, and shape manipulation (Figure 4).

Function	Purpose	Sensors	Procedure
Push/Pull	Measure force	Load cell	Move the handle while shaft collar modulates the resistance
Grip	Measure grip strength	Load cell	Grasp the bottle
Twist	Measure rotation of hand	Rotary potentiometer	Remove the bottom cap on bottle
Bottle Movement	Monitor gross UL movement	Timing buttons	Move the whole bottle
Shape Manipulation	Assess tactile function	Detector switches	Insert shapes into appropriate wells

Table 1: Summary of the Handy Gym Functions

Data from all five functions are acquired by an Arduino© while a MATLAB® script processes and displays the data on an onscreen GUI. The software can engage multiple sensors simultaneously allowing the therapist to focus on bimanual coordination by having the patient perform multiple functions simultaneously. The software displays temporal data and force generated by the patient. **In addition to providing quantitative metrics, the Handy Gym is portable, easy to use, and multifaceted.**

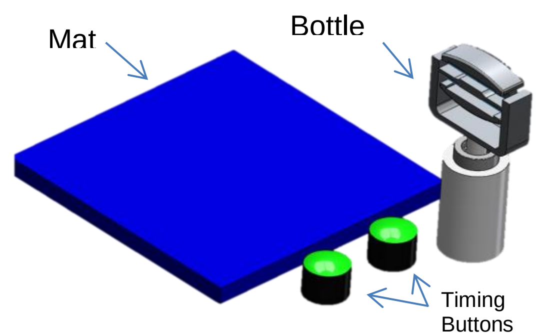


Figure 3: The Handy Gym System

Figure 4: From left to right, this panel highlights the push/pull, grip, complete system, and shape manipulation/twist.

Portable

The closest competing products are bulky or have multiple removable pieces. The Simulator II (BTE™) is an upper limb training system that is six feet tall and six feet wide, weighing 575 lbs. Although the Simulator II can simulate a variety of daily activities by purchasing a multitude of attachments, many of these additions make the overall system bigger, require extra storage space, and increase the cost of the system. In a clinical setting, space is an important consideration. By comparison, the Handy Gym is 12 by 4 by 4 inches weighing 2 lbs. and comes with a mat and two timing buttons. The small size of the Handy Gym allows it to be easily moved from one space to another. This size advantage allows the therapist to use this device in an in-patient or out-patient setting or in a mobility-limited patient's home. The accompanying software can be run on a laptop thus not requiring a bulky computer system. Therefore, the Handy Gym can be used in any therapy setting.

Ease of Use

In speaking with a practicing therapist, an important factor cited by therapists for utilizing a new device is its ease of use and integration into their current practice. During a typical 30-60 minute therapy session, no time should be wasted in setting up and shutting down the device.

The learning curve to implement the device should also be minimal. Finally, navigating the software and different functions of the device must be intuitive and quick to initiate. The minimal components of the Handy Gym and singular USB connection to a PC or laptop require only a few minutes to set up. Tasks supported by the device are intuitive and easy to learn, such as pushing and pulling a handle, placing shapes into a shape well, and rotating the cap. Also, the software has only two main screens to navigate. The GUI displays relevant data with minimal buttons. The software automatically obtains temporal measurement when the device is used in therapy, freeing the therapist from using a stop watch or other timing devices. The simplicity of the Handy Gym reduces the need for extensive support for the device after the point of purchase.

Multi-faceted

The Handy Gym provides five different functions that therapists can use to assess patient mobility. Current products at most replicate one task – e.g. pinch grasping during the 9-Hole peg test – or require many different attachments to be purchased to simulate different motions. All functions of the Handy Gym are built into the device and require no extra parts or therapist setup time. The variety of functions is ideal for UL therapy because the patient population is very heterogeneous in the degree of UL impairment. Thus, depending on a patient's level of impairment, the therapist can use particular functions on the Handy Gym. Unlike current devices, the Handy Gym can modulate resistance for the Push/Pull function, allowing the therapist to make the task more challenging as the patient improves over time.

Evidence of Working Prototype

Shaft Collar

The shaft collar (Figure 4) modulates the resistance for the Push/Pull task. The therapist controls this resistance by turning a set screw located on the shaft collar. Resistance was increased from zero to over ten pounds by turning the screw on the shaft collar. A plot (Graph 1) displaying the relationship between screw revolution and resistance was created. Preliminary wear testing of the shaft collar was conducted by manually cycling the push/pull 100, and 200 times while recording the resistances (Graph 2). ANOVA was performed comparing average resistances across the 100 and 200 cycles. Obtaining $p>0.05$, the null hypothesis was accepted that there are no significant differences in resistance across the 100 and 200 cycles of testing. These results verify the shaft collar's ability to modulate resistance to the push/pull function from zero to ten pounds. Preliminary wear testing also confirm the shaft collar system to be robust over several cycles.

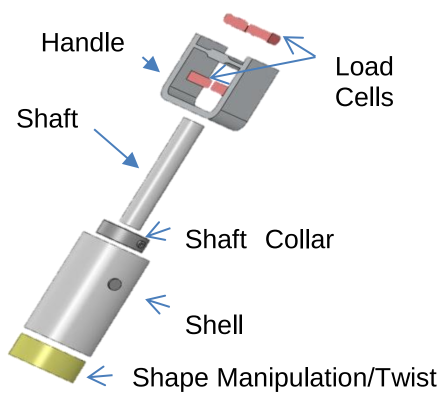
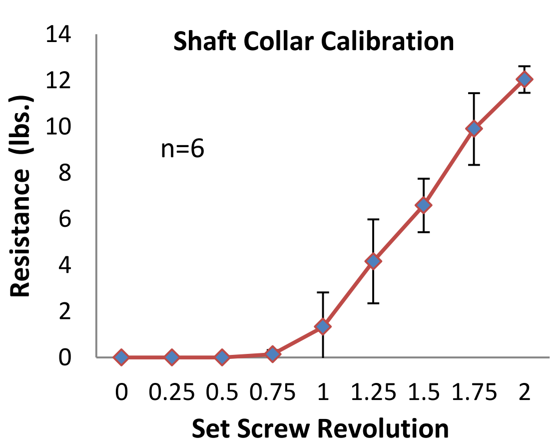
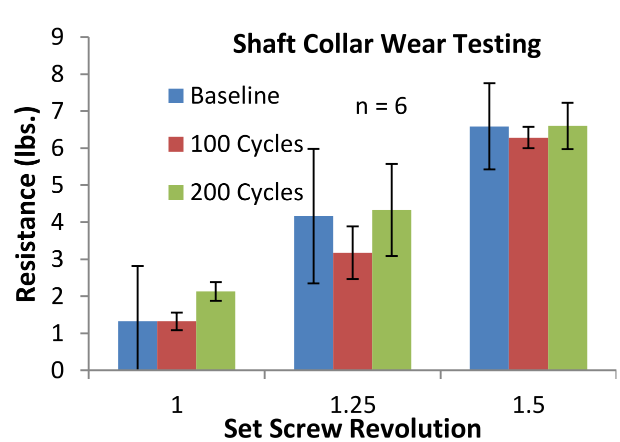


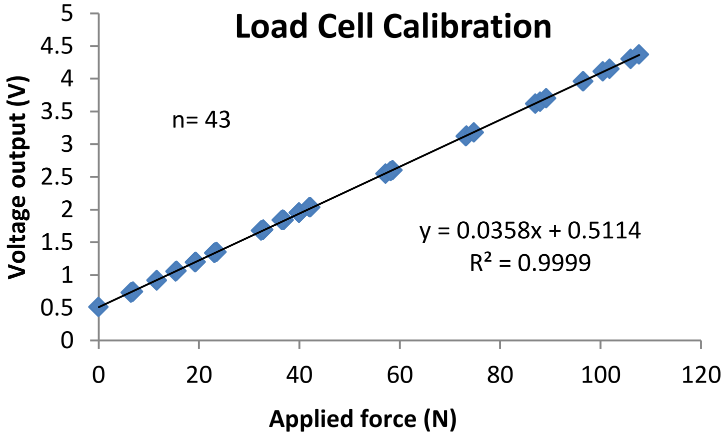
Figure 5: Bottle Schematic



Graph 1: Baseline calibration curve



Graph 2: Results from manual wear tests



Graph 3: Load cell calibration curve

Load Cell

Load cells are used to acquire user generated forces. A TestResources materials testing machine was used to apply known compressive forces to the load cells, and the voltage output from the load cells was recorded. A representative calibration curve shown confirms that response is highly linear (Graph 3). From this relationship a simple linear equation was derived to convert Volts to Newtons.

GUI Feedback

The GUI is an important facet of the overall design. Therefore, we obtained user feedback on its functionality. Four male college students were asked to interact with the Handy Gym in a mock therapy session and feedback was collected at the end. Three functions were tested: shape, grip, and push/pull.

The average time it took the users to complete all of the 3 tests was 324 ± 14 s. The most commonly failed instructions were locating how long the test took overall, finding out how long it took for the triangle shape to be inserted, saving data, and recording whether the push and pull forces were on different lines in the graph. All users were able to complete all of the tests despite not being able to record this information or save the data. Table 2 summarizes the results of the user survey with a scale of 1 (worst) to 5 (best). We conclude that the software is easy to navigate and learn although some adjustments are necessary.

Category	Score (mean ± S.D)
Ease of Learning the Software	4.25 ± 0.5
Ease of Navigating the Software	4.75 ± 0.5
Ease of Following Testing Instructions	3.5 ± 1.3
Usefulness of the Software Layout	4.125 ± 0.25
Ease of Interpreting the Results	3.875 ± 0.25

Table 2: User survey. n = 4. Categories scored from 1 (worst) to 5 (best).

Shape Manipulation

The shape manipulation task involves three small objects, a square, triangle and circle that must be inserted into their appropriate shape wells. Upon insertion of the shapes the corresponding LED light will illuminate confirming proper placement of the shape. Meanwhile, the software records the time from the start of the task to the end when the last shape is inserted. Additionally, the time in between the shapes are also calculated and displayed on the GUI. See Figure 6 demonstrating the LED light illuminating upon proper insertion of a shape.

Figure 6: Shape Manipulation.

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