Dynamic Weighted Bar for Upper Limb Rehabilitation

Taylor C. Hornung
Department of Mechanical Engineering,
The Pennsylvania State University,
University Park, PA 16802
e-mail: tch5085@psu.edu

Stephen J. Piazza
Department of Kinesiology,
The Pennsylvania State University,
University Park, PA 16802
e-mail: piazza@psu.edu

Everett C. Hills
Department of Physical Medicine and Rehabilitation,
The Pennsylvania State University,
Hershey, PA 17033
e-mail: ech14@psu.edu

Jason Z. Moore
Department of Mechanical Engineering,
The Pennsylvania State University,
University Park, PA 16802
e-mail: jzm14@psu.edu

This paper explores the design of a dynamically weighted therapy bar, which can provide real-time quantitative performance information and adjustments during rehabilitation exercise. In contrast, typical therapy equipment is passive, offering no feedback to the patient or clinician. The dynamic weighted bar (DWB) was designed and fabricated containing an inertial sensor which tracks the orientation of the bar and adjusts the position of an internal weight accordingly, in turn providing a targeted force imbalance between the patient's two arms. Step input experiments were performed on the device while it was held in various stationary positions. The DWB was able to successfully function and transmit motion information. It was able to produce a center of mass shift of 101.6 mm, and a complete travel time between 0.96 s and 1.41 s over the entire length. The use of the DWB device can offer many benefits during rehabilitation including access to more quantitative information for clinicians as well as the potential for more personalized therapy programs. [DOI: 10.1115/1.4033451]

Keywords: medical robotics, rehabilitation devices, therapy, sensors/actuators

1 Introduction

In the U.S., there are a total of 795,000 new and recurrent cases of stroke each year, with 610,000 of them being first time attacks [1]. According to data from 2006–2010, the overall prevalence of stroke also continues to remain roughly unchanged [1]. Stroke is a serious illness, accounting for over 16% of the deaths attributable to cardiovascular diseases, second only to coronary heart disease [1]. Unfortunately, it is also the leading cause of long-term disabilities for those that survive. After experiencing a stroke, approximately 50% of people suffer from hemiparesis, a weakness in half of the body, 30% struggle to walk, and 46% suffer from cognitive deficits [1,2].

Conventional physical therapy for stroke rehabilitation often utilizes basic nonrobotic technology. For upper body training, elastic bands and weighted bar training are especially common. In weighted bar training, a patient is instructed to lift a weighted bar while gravity applies resistance. These nonrobotic options for therapy can be very effective to help patients regain strength and flexibility [3,4]. However, these devices suffer from three key limitations: the devices cannot be easily adjusted for different levels of impairment, their functional relevance to activities is indirect, and they provide very little information to patient or therapist about progress [5].

Much research has focused on automated robotic systems for characterizing patient motion during poststroke recovery, primarily for automating clinical evaluation procedures. By automating labor intensive tasks, clinicians can focus on providing quality care that is targeted to the specific individual. Automated testing also helps eliminate biases caused by human assessment and helps standardize exercise procedures. However, utilization of this data for real-time refinement of exercise methods in rehabilitation is still lacking. Many current methods of robotic-assisted recovery focus not on new methods of rehabilitation but on augmenting or automating current methods [6–9]. In these current methods, robotic devices are used to apply additional loads or constraints on the patient, providing higher consistency over longer periods of time which can improve a patient's overall recovery [10,11]. Currently, there is a large disparity between typical rehabilitation equipment, which may range from simple items, such as weights for resistive training, to advanced robotic systems used in research labs. Examples of high-end systems used in research are the MIT-Manus [12], ARM-guide [13], and mirror-image motion enabler [14] for upper extremity training. Some of the major drawbacks to these advanced systems include their high cost and complexity which restricts their wide use in the medical field outside of research [15].

The DWB, illustrated in Fig. 1, is a low cost easy to use automated physical therapy training device that is able to continuously collect information about patient progress and is able to shift the center of mass in response to patent performance. To utilize this device, a patient holds the bar and lifts it up and down. Unlike conventional weighted bar training, a wealth of movement data, including acceleration of movement and pitch of the bar during lift, is able to be collected during the therapy session and then analyzed. Unlike high-end robotic therapy devices, this device is fairly inexpensive, containing approximately $350 in components. The DWB can also be programed to dynamically shift the center of mass of the bar during physical therapy based on the angle of the bar. The specific benefits of this have yet to be studied but this dynamic weight shift could induce perturbations into the training which have been shown to be beneficial in lower limb training [16]. The dynamic weight shift can also dynamically reduce the amount of energy needed to be input by the user to physically lift the device, thereby allowing for a more customized therapy for the user.

This paper outlines the design and testing of the DWB device. Section 2 discusses the design and fabrication of the device, modes of operation, and clinician interface. The experimental

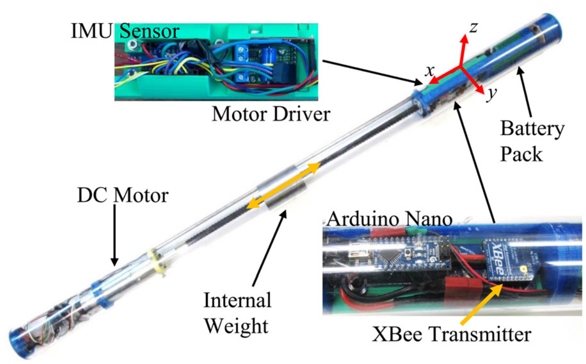

Fig. 1 DWB device

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setup is outlined in Sec. 3 followed by the results of those experiments in Sec. 4, and finally, conclusions are presented in Sec. 5.

2 Dynamic Weighted Bar Design

2.1 Components of Dynamic Weighted Bar. The DWB, illustrated in Fig. 1, is constructed using a 0.91 m long, clear polycarbonate plastic tube with a 50.8 mm outer diameter. The bar is designed to be similar in size to that of standard therapy bars so it can be held comfortably when clasped in a patient's hands. To provide a dynamic center of mass, a mobile central weight made of carbon steel is used. This, when coupled with the other components of the device, makes the bar weigh 20.5 N; comparable to typical physical therapy bars. The central weight weighs 5.2 N and is connected to a Torqspline® lead screw with a 25.4 mm lead and a stainless steel guiderail that also acts as a wire conduit. A Teflon sleeve is mounted inside the weight to allow it to slide smoothly along the guiderail. The high thread lead of the screw permits the weight to traverse its full travel length of 330 mm in only 13 revolutions of the lead screw.

The motor selected to drive the lead screw is a Pittman (Harleysville, PA) 12 V Brushed DC Motor, with a Pittman 4:1 Planetary Gearbox. The gearbox shaft is then coupled directly to the lead screw. The compact motor offers 0.059 N·m of continuous torque (0.2365 N·m peak) at 3815 rpm (6055 rpm no load) prior to the gear reduction. The minimum torque required by the motor, T, is computed using Eq. (1), where L is the lead of the lead screw, η is the efficiency (typically 60–75% for Torqspline® lead screws), g is the gravity, θ is the pitch angle the bar is tilted, m_w is the mass of the moving central weight, a_w is the acceleration of the central weight, and I is the moment of inertia of the lead screw (2.58 kg mm^2). For a desired acceleration of 0.1 s to reach maximum travel velocity of 0.404 m/s when the bar is vertical ($\theta = 90$ deg) requires a peak torque of at least 0.013 N·m and 0.0043 N·m of peak torque when the bar is in a horizontal orientation ($\theta = 0$ deg). This is less than the continuous torque of 0.059 N·m that can be produced by the motor. The motor is more than adequate to quickly move the weight from one extreme to the other in less than 1 s of travel time at nominal power

$$T = \frac{m_w L\left(a_w + g\sin(\theta)\right)}{8\ \pi\ \eta} + \frac{\pi\ I\ a_w}{2L} \tag{1}$$

The steady-state angular velocity of the motor, ω, can be found by Eq. (2). This accounts for the effects of gravity, the gearing of the motor, and the efficiency of the lead screw, where V_s, K_T, K_v, and R are the supplied voltage, motor's torque constant, voltage constant, and resistance, respectively. Note this equation does not include additional frictional resistance of the weight on the slide. This equation also does not include dynamic forces on the weight that would be created by rotation and acceleration of the bar by the user

$$\omega = \frac{V_s - m_w\ g\ \sin(\theta)\ \dfrac{L\ R}{8\ \pi\ \eta\ K_T}}{K_v} \tag{2}$$

An Arduino, Arduino Nano, and XBee wireless transmitter are used as the onboard controller in the DWB. The compact size of the Arduino Nano allows it to fit easily within the 44.5 mm inner diameter of the bar. The XBee replaces the need for a wired USB cable and allows all the data collected from the bar to be sent wirelessly to a computer. A nine degrees-of-freedom IMU sensor is embedded within the bar. The sensor contains an Analog Devices (Norwood, MA) three-axis accelerometer, an InvenSense (Sunnyvale, CA) three-axis gyroscope, and a Honeywell (Morristown, NJ) magnetometer. A 15 A motor driver is selected to interface with the DC motor. The driver has a 5.5–30 V input voltage range and can safely supply up to 15 A of current. The electrical components allow for the control of the motor, sensing of the bars orientation and acceleration, and wireless communication and storage of the data.

2.2 Mode Selection. The bar offers three modes of operation, set by the controls contained in the bar's endcap, as shown in Fig. 2. The modes are weight high mode, weight low mode, and manual mode. In the weight high mode, the internal weight will shift to the higher side of the bar when tilted. The center position can be biased to either side using the weight position center gravity (CG) knob. This mode allows for active rebalancing of the bar if the weakened arm is unable to maintain pace with the stronger limb. In weight low mode, the internal weight shifts to the lower side of the bar when tilted. In the manual mode of operation, the internal weight remains stationary within the bar. Its stationary position is set using the weight position knob. If the weight is set to the exact center of the bar, this mode behaves the same as a typical passive therapy bar. When the weight is biased to one side, this mode behaves as a bar with nonuniform weight distribution.

The aggressiveness knob is a five-position rotary switch whose value is read as an analog signal. Each aggressiveness value is set to a predefined angle ranging from 5 deg to 20 deg corresponding to the maximum pitch the bar can reach before the weight will traverse entirely to one side, as illustrated in Fig. 3. This defines the ± limit (angle) values within the program. For modes other than manual, the target position for the weight is mapped directly from the current pitch of the bar, relative to the ± limit values, to a position between the extremes of the travel length, right and left ends of the bar, relative to the center position determined by the CG knob. The final target value is then passed to the feedback controller.

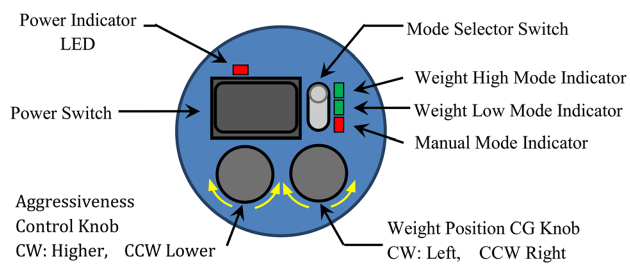

Fig. 2 Diagram of controls endcap for DWB

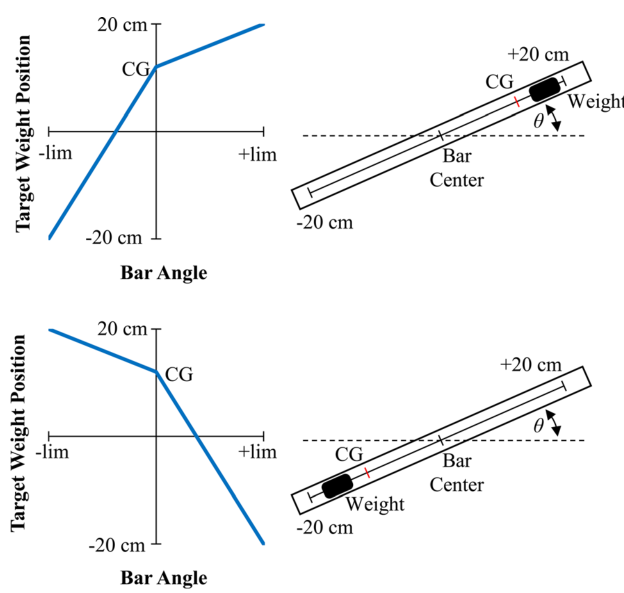

Fig. 3 Mapping (left) and diagram (right) of bar angle to target weight position for CG knob = 0.6, weight high mode (top), and weight low mode (bottom)

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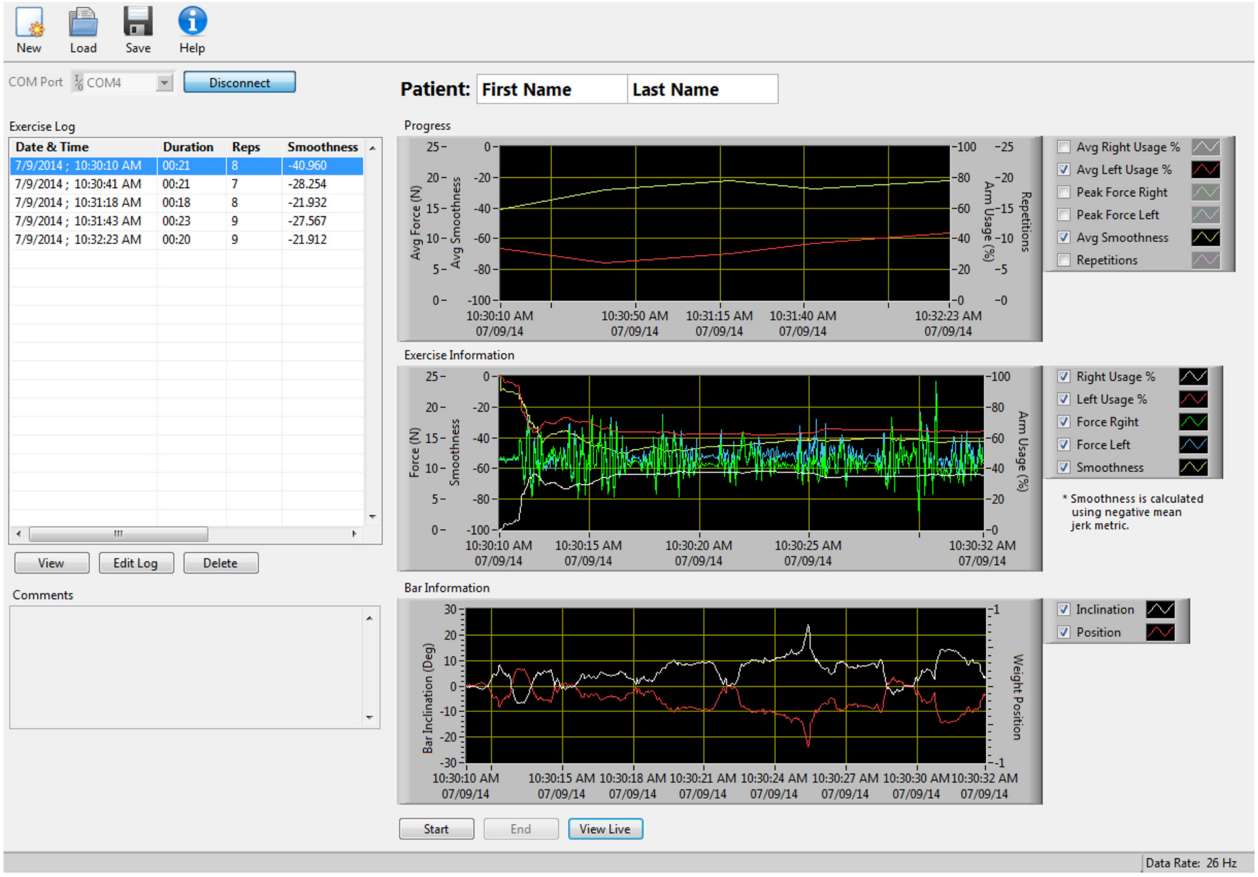

Fig. 4 DWB clinician interface

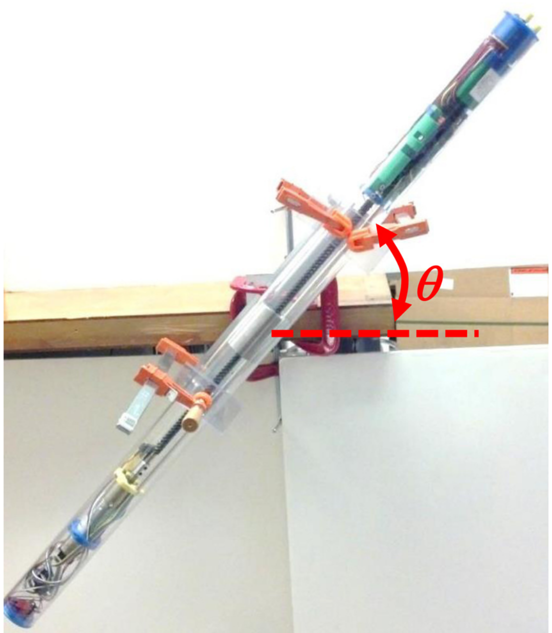

Fig. 5 DWB experiment fixture

2.3 Clinician Interface. The clinician interface for the DWB is shown in Fig. 4. This allows a clinician to easily monitor their patient's exercise as well as track the patient's progress over the course of their recovery. There are three graphs which display information about the bar. The bottom two graphs display a live feed of the bar's pitch angle, the position of the weight inside the bar, the percentage of work by each arm, the force experienced by each arm, and the smoothness of motion. The top graph displays averages from previous exercises and is used for easy tracking of a patient's progress during recovery.

3 Experimental Setup

An experiment was performed to evaluate the response time of the device. For this, the bar was mounted to a rigid fixture as shown in Fig. 5. The bar was set to a specified angle between -90 deg and $+90$ deg in increments of 20 deg, and the weight was commanded to move to the other end of the bar. Five sample runs were performed at each angle. At the end of travel, the weight engages the limit switch inside the bar since the target is actually slightly past the end of travel.

4 Results and Discussion

Figure 6 shows the response of the DWB to a step input across the entire travel length of the bar for various orientations of the device. The highly linear trajectories demonstrate how the motor moves the weight at its maximum velocity throughout the duration of travel. The curves illustrate the difference in response times when the motor must move the weight against varying amounts of gravity. The slight oscillations in these trajectories are caused from the vibrations in the experimental setup. With gravity assisting, the rise time is 0.96 s, as compared to 1.41 s with movement against gravity. For pitch angles greater than zero, the device performs equally fast, seen by the plateau in rise times illustrated in Fig. 7. The primary limiting factor on these rise times is the firmware limit which saturates the motor power output to 50%, effectively restricting the maximum velocity of the weight to 345 mm/s with gravity and 234 mm/s against gravity.

The bidirectional shift in the center of weight (COM) of the bar, d, can be calculated by Eq. (3) given the weight of the bar,

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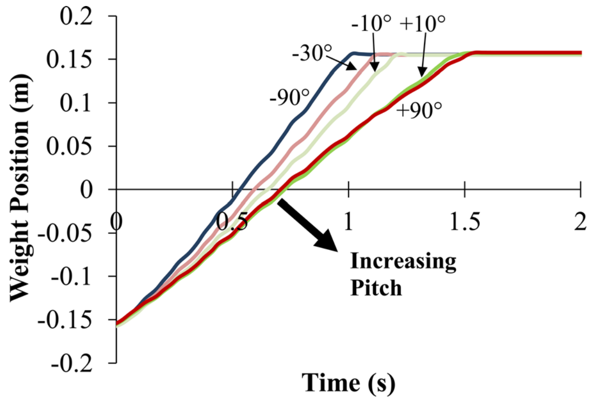

Fig. 6 Step input response of DWB for various bar pitch angles

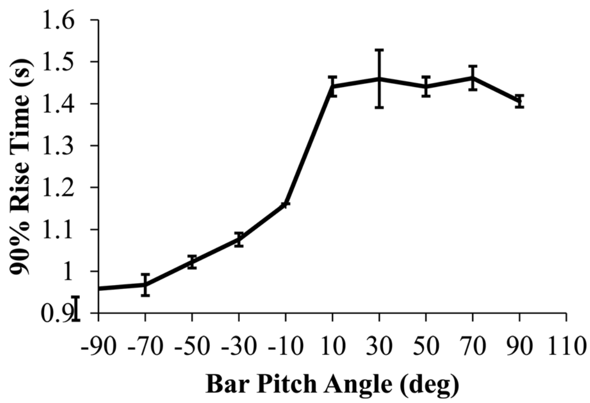

Fig. 7 Rise time of weight position based on pitch angle

W_{BAR}, the weight of the moving mass, W_{wt}, and the distance the weight is from the center of the bar, D_w. With the current design, a maximum COM shift of $\pm$ 50.8 mm can be obtained. In this configuration, the bar can provide 39.3–60.7% weight distribution between the two hands. Increasing the travel length of the weight or increasing the amount of weight moving would increase the achievable COM shift

$$d = \frac{W_{wt}}{W_{\mathrm{BAR}} + W_{\mathrm{wt}}} * D_W \quad (3)$$

5 Conclusions

A DWB for physical therapy was successfully designed, fabricated, and tested. This novel device is capable of shifting the center of mass by 101.6 mm in response to the pitch of the bar. This weight shift is able to produce a distribution of up to 39.3% weight in one hand and 60.7% in the other hand. This device was able to successfully transmit and store data of the bar's pitch angle, the position of the weight inside the bar, the percentage of work by each arm, the force experienced by each arm, and the smoothness of motion. The DWB provides active therapy that responds directly to patient performance. Further experimentation will be performed to determine the potential benefits of this active training method. The DWB has the potential to shorten patient recovery time by providing clinicians with patient performance information which will allow the development of more patient-specific therapy programs.

Nomenclature

a_w = acceleration of the central weight
d = bidirectional shift of the bars center of mass
D_w = distance the weight is away from the center of the bar
g = acceleration of gravity
I = moment of inertia of lead screw
K_T = motor torque constant
K_v = motor voltage constant
L = lead of the lead screw
m_w = mass of the central weight
R = motor resistance
T = motor torque
V_s = voltage supplied to motor
W_{BAR} = weight of the bar
W_{wt} = weight of the moving mass
η = lead screw efficiency
θ = pitch angle, angle bar is tilted
ω = steady-state angular velocity of the motor

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