JRRD
Volume 51, Number 5, 2014
Pages 711–726

Design and evaluation of prosthetic shoulder controller

Joseph E. Barton, PhD;[1*] John D. Sorkin, MD, PhD[2]
[1]Department of Physical Medicine and Rehabilitation, Northwestern University, Chicago, IL; and Rehabilitation Institute of Chicago, Chicago, IL; [2]Geriatrics Research, Education, and Clinical Center, Baltimore Department of Veterans Affairs Medical Center, Baltimore, MD

Abstract—We developed a 2-degree-of-freedom (DOF) shoulder position transducer (sensing shoulder protraction-retraction and elevation-depression) that can be used to control two of a powered prosthetic humerus' DOFs. We also developed an evaluation protocol based on Fitts' law to assess the performance of our device. The primary motivation for this work was to support development of powered prosthetic shoulder joints of a new generation of prosthetic arms for people with shoulder disarticulation and very high-level transhumeral amputation. We found that transducers that provided resistance to shoulder movement performed better than those providing no resistance. We also found that a position control scheme, where effector position is proportional to shoulder position, performed better than a velocity control scheme, where effector velocity is proportional to shoulder position. More generally, our transducer can be used to control motion along any two DOFs. It can also be used in a more general 4-DOF control scheme by sequentially controlling two DOFs at a time. The evaluation protocol has general applicability for researchers and practitioners. Researchers can employ it to compare different prosthesis designs and control schemes, while practitioners may find the evaluation protocol useful in evaluating and training people with amputation in the use of prostheses.

Key words: amputation, Fitts' law, index of difficulty, linear mixed-effects model, position control, prosthetic arm, prosthetic arm control, resistive feedback, shoulder range of motion, velocity control.

INTRODUCTION

A major shortcoming of prostheses for people with very high-level upper-limb amputation (individuals who have lost 80 percent or more of their humerus) is the inability to quickly and effortlessly position a prosthetic hand in space so that it can grasp and manipulate objects [1]. In the intact arm, this is accomplished through the control of the humerus' three degrees of freedom (DOFs) (flexion-extension, abduction-adduction, and internal-external rotation) via the shoulder complex (the scapula, clavicle, humerus, and approximately 30 different muscles and ligaments in the chest and back). Shoulder movement would be an obvious choice to control a prosthetic humerus. Though much is lost with the arm, much still remains (in particular, many of the sensory feedback mechanisms located throughout the shoulder complex) that could restore some degree of natural functionality to the task.

Until recently, though, this has been a moot point because of the primitive state of prosthetic arms (compared with anatomical arms), and in particular, the unavailability

Abbreviations: DOF = degree of freedom, EMG = electromyography, FSR = force sensitive resistor, HCI = human computer interface, ID = index of difficulty, SE = standard error, ToMPAW = Totally Modular Prosthetic Arm with high Workability.

***Address all correspondence to Joseph E. Barton, PhD; University of Maryland School of Medicine, Department of Neurology, 100 Penn St, Room 107, Baltimore, MD 21201; 410-706-5211; fax: 410-706-6387.**
Email: JBarton@som.umaryland.edu
http://dx.doi.org/10.1682/JRRD.2013.05.0120

of powered prosthetic shoulder joints. Absent a powered shoulder joint, the humerus is controlled in a very crude fashion. Typically, the shoulder joint is first unlocked via a switch so that it swings freely, and then the person with amputation positions it with his or her intact arm (or, in the case of bilateral amputation, by bending at the waist to position the upper arm via gravity). When the desired position is reached, the shoulder is then locked in position. Control of a full upper-limb prosthesis is thus extremely slow, cumbersome, and very unnatural. This is reflected in its low usage rates and in the low levels of satisfaction reported by people with amputation. Of people with upper-limb amputation, 60 percent or more use a cosmetic as opposed to a functional prosthesis [2–4], an outcome that Kejlaa regards to be a clinical failure [5]. Loss of a limb and the inability to restore its functionality leads to loss of self-esteem, high levels of borderline or significant anxiety, and depression among people with upper-limb amputation [4]. It has also been found that 65 percent or more of this population change jobs as a result of their amputation (usually to a lower-paying job), and that as many as 25 percent become unemployed [2,4,6–7].

Perhaps the first modern upper-limb prosthesis was the IBM arm introduced by Alderson in 1954 [8]. This was an electrical prosthesis with hand prehension, wrist rotation and flexion, and elbow rotation. In the 1970s and 1980s, Nightingale and Swain developed control systems for a fully articulated artificial arm, which included a multi-DOF prosthetic hand [9–10]. They employed a hierarchical approach in which the user commanded gripping tasks with three body movements to control the arm and one electromyography (EMG) signal to control the hand. Lower-level adaptive control systems then autonomously controlled arm trajectory and gripping based on information provided by a gyroscope located in the supporting harness and touch and slip sensors located in the palm of the hand. The Edinburgh Modular Arm System, whose development began in 1990, was one of the first complete electrical prosthetic arms, incorporating a powered shoulder controlled by a pressure pad located inside the socket to which the prosthesis was attached [11]. The Edinburgh Arm in turn formed the basis for the ToMPAW modular prosthesis (Totally Modular Prosthetic Arm with high Workability) [1]. The ToMPAW Arm's shoulder was controlled by a joystick modified to provide force feedback to the user, which sensed movement of the acromion process. Neither the Edinburgh nor the ToMPAW Arms were introduced commercially.

In the last few years, development of a new generation of very high-level prostheses for commercial use began. Troncossi et al. developed a 2-DOF powered shoulder joint that allows the elevation of the upper arm in any vertical plane passing through the joint's center of rotation [12]. The DARPA Modular Prosthetic Arm incorporates a hand with multiple DOFs as well as a powered shoulder joint and humeral rotator [13]. Their widespread introduction could substantially improve patient satisfaction and usage and lead to more positive psychological, social, and employment-related outcomes.

Historically, shoulder movement has been used to control a prosthesis' more distal elements in order to augment the limited number of control signals available for this purpose. Recent innovations such as targeted re-enervation surgery [14], pattern recognition-based myoelectric control [15], and implantable myoelectric sensors [16], however, promise to create additional sources of control signals, freeing the shoulder to control humeral function. Based on these developments, work has begun to identify the most efficacious way to apply the shoulder to humeral control. The traditional method of control involving the shoulder employs pressure pads, rocker switches, and force sensitive resistors (FSRs), etc., mounted on the socket, which the shoulder presses against. In 1972, however, Bayer et al. developed a 2-DOF shoulder position transducer employing a load cell to sense shoulder motion of patients with quadriplegia in controlling powered wheelchairs [17]. A more recent study by Lipschutz et al. compared a prosthetic shoulder control scheme employing FSRs and a rocker potentiometer with one employing a two-axis joystick [18]. The authors found that their subjects (3 nondisabled subjects and 2 subjects with shoulder disarticulation) overwhelmingly preferred the joystick, primarily because two DOFs can be controlled simultaneously and the shoulder's entire range of motion can be utilized. This led to faster, more precise, and more intuitive control on the part of users and noticeably smoother and more fluid movements of the prosthesis. One drawback of this arrangement is that since the joystick offers no resistance to movement, thus tactile force feedback is lacking.

Though users' subjective evaluations are valuable, and in this particular case, the superior control scheme was evident based on observation, it would be desirable to augment these with a more objective, quantitative method to evaluate and compare different control schemes. We have developed such a method based on the work of Fitts [19], who introduced a quantitative measure of the difficulty in moving from a starting point to a particular target.

Fitts' law has been used extensively in the evaluation of human computer interfaces (HCIs) such as computer mice, keyboards, and graphical user interfaces [20]. A number of recent studies have demonstrated its applicability to prosthetic control applications. Researchers used it to evaluate EMG-based HCI control schemes [21–23]. Scheme et al. employed it in the context of pattern recognition-based myoelectric control to evaluate and compare algorithms that distinguish and reject anomalous muscle contractions [24–26].

Our study had three goals. The first and primary goal was to build upon the work of Bayer et al. [17] and Lipschutz et al. [18] and develop a shoulder position transducer that can be used in a feedback control scheme, where feedback to motion is provided by a resistive force proportional to shoulder displacement. Accomplishing this goal required knowledge of the shoulder's range of motion as well as the forces it is capable of generating in each direction, which led to our second goal, the quantification of the shoulder's range of motion and measurement of the forces the shoulder can comfortably generate at the point of the acromion process. The third goal of this study was to develop a method to quantitatively assess prosthesis control.

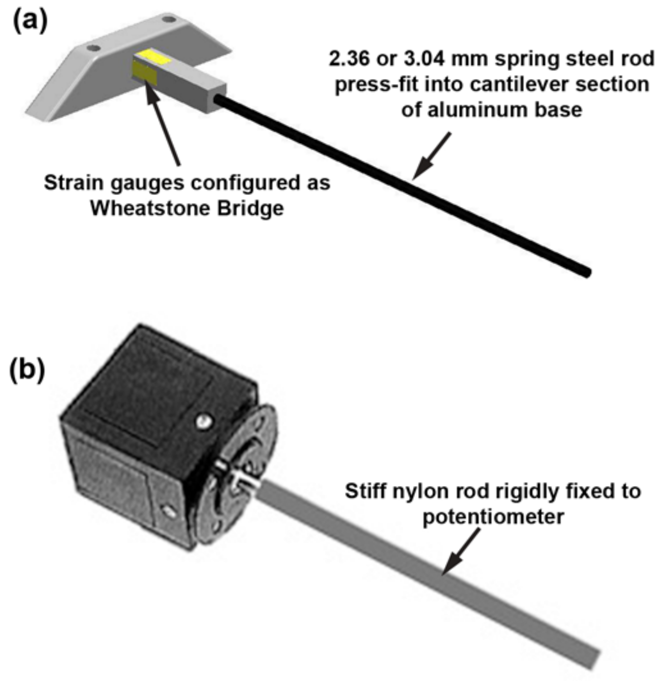

Figure 1.
Transducer assembly schemes. (**a**) One-piece aluminum base/cantilever section and steel rod. (**b**) Two-degrees-of-freedom potentiometer.

METHODS

We developed and tested three control assemblies designed to convert shoulder motion into control signals and a body socket designed to be worn on the side of the thorax that had experienced the amputation. Each assembly was connected to the body socket (socket 1) and sensed shoulder motion via one of two steel rods or a nylon rod. The assemblies incorporating the steel rods provided proprioceptive feedback and tactile feedback (the latter by resisting shoulder motion), while the assembly incorporating the nylon rod provided only proprioceptive feedback.

Study Aim 1: Develop Shoulder Position Transducer

The first two assemblies consisted of one of two steel rods (either 2.36 or 3.04 mm in diameter) rigidly press-fit into the cantilever section of a one-piece machined aluminum base (**Figure 1**) such that there was no movement of the rods with respect to the base at their points of attachment. Shoulder movement in the anterior-posterior and the superior-inferior directions caused bending of the steel rod, and in turn, bending of the aluminum base's cantilever section, which was sensed by strain gauges attached to the latter, producing a control signal. The difference in diameter of the steel rods allowed for two levels of resistance to shoulder movement. These assemblies will be referred to as the "236 steel rod" and the "304 steel rod," respectively. The third assembly (**Figure 1**) consisted of a potentiometer having two DOFs (i.e., anterior-posterior and superior-inferior), which was attached to a stiff nylon rod. It will be referred to as the "joystick." This assembly provided no resistance to shoulder movement.

The steel or nylon rods extended from their respective assemblies laterally from their point of attachment toward a steel eyebolt connected to an adjustable rigid strap located at the right acromion process (**Figure 2**). The strap to which the eyebolt was attached wrapped securely around the right shoulder and armpit at the acromium process and moved with the shoulder independently of the body socket. Thus, as the subject moved his or her right shoulder, the rod was bent by the eyebolt in the direction of shoulder motion while the base of the

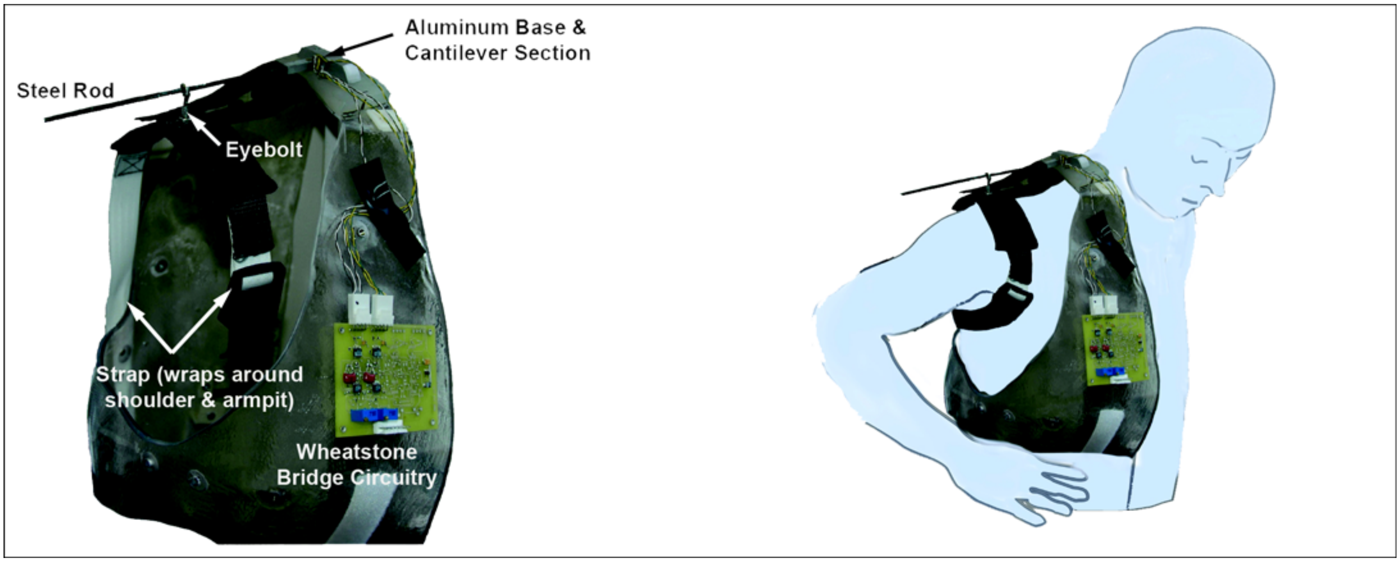

Figure 2.
Socket 1 with steel rod assembly attached. Socket fits over subject's right shoulder as subject faces out of figure to reader's right. Subject's right arm extends through opening. Strap is secured around right shoulder at acromion process. Eyebolt is securely fixed to strap and moves with shoulder. As subject moves shoulder, eyebolt bends steel rod that passes through it. This bending is sensed by strain gauges attached to cantilever section of aluminum base and converted to voltage signal by Wheatstone Bridge circuitry. Bridge's voltage, which is proportional to rod bending, is used to control movement of prosthetic arm, or in this case, cursor on display.

transducer assembly remained fixed with respect to the rest of the body via attachment to the body socket. Both the socket and eyebolt were strapped securely to the torso and shoulder, respectively, and there was no visible movement of either with respect to the body parts to which they were attached. Because the rods were free to slide through the eyebolt, they were not stretched or compressed by the action of the shoulder; they were only bent with respect to their base.

For the steel rod assemblies, shoulder motion producing bending of the steel rods was sensed by two sets of strain gauges configured as Wheatstone Bridges, which were mounted on each of two perpendicular faces of the cantilever section of the aluminum base (**Figure 1**). The Wheatstone Bridges produced voltages (control signals) proportional to the movement of the right shoulder in the anterior-posterior and superior-inferior planes. Unlike the steel rod assemblies, the joystick assembly provided no resistance to motion of the nylon rod at its point of attachment. Motion at the joystick's point of attachment varied the electrical resistance proportionately to displacement along either the anterior-posterior or superior-inferior planes, providing a control signal.

When designing the steel rod assemblies, we needed to select rods that would offer varying levels of resistance to shoulder motion. We first chose spring steel for the rod material because of its ready availability. To allow us to choose rods of appropriate diameter (i.e., stiffness), we then modeled the assembly as a two-section cantilever beam (**Figure 3**). L_C represents the length of the cantilever section of the aluminum base, and L_S represents the length of the steel rod. The deflections y_C and y_S of the two sections in response to the application of force (F) at the eyebolt are given by **Equation 1** [27]—

$$y_c = \frac{1}{E_c I_c}\left[\frac{F L_{cs} x_c^2}{2} - \frac{F x_c^3}{6}\right],$$

$$y_s = \frac{1}{E_s I_s}\left[-\frac{F x_s}{6} + \frac{F L_s}{2}\right] x_s^2 + \frac{1}{E_c I_c}\left[F L_{cs} L_c - \frac{F L_c^2}{2}\right] x_s + \frac{1}{E_c I_c}\left[\frac{F L_{cs} L_c^2}{2} - \frac{F L_c^3}{6}\right]. \quad \textbf{(1)}$$

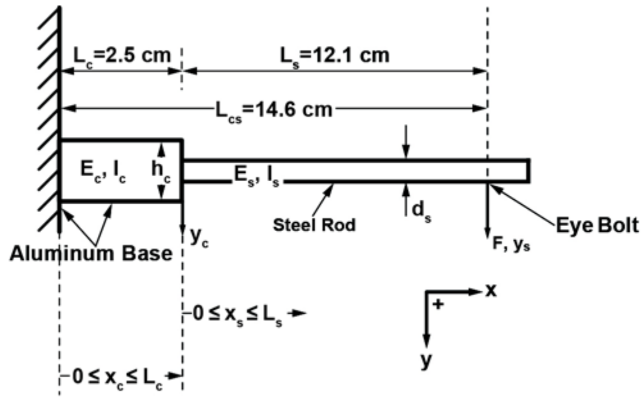

Figure 3.
Two-section cantilever model of steel rod assembly. d_S = diameter of steel rod, E_C = Young's modulus of aluminum cantilever section, E_S = Young's modulus of steel rod, F = force, h_C = side dimension of square cantilever section of aluminum base, I_C = cantilever section's area moment of inertia for bending, I_S = steel section's area moment of inertia for bending, L_C = length of cantilever section of aluminum base, L_S = length of steel rod, L_{CS} = combined length of cantilever section and steel rod ($L_C + L_S$), x_C = distance from base of cantilever section at which deflection y_C is computed per **Equation 1**, x_S = distance from base of steel rod at which deflection y_S is computed per **Equation 1**, y_C = deflection of cantilever section at x_C, y_S = deflection of steel rod at x_S.

where E_C and E_S = the Young's modulus of the aluminum cantilever section and steel rods, respectively; I_C and I_S = the cantilever section's and rod's area moments of inertia for bending, respectively; and L_{CS} = the combined length of the cantilever section and steel rod ($L_C + L_S$). The maximum deflection (y_S) at the end of the control rod ($x_C = L_C$ and $x_S = L_S$) resulting from the application of force (F) at the eyebolt ($x_C = L_C$ and $x_S = L_S$) is given by **Equation 2**—

$$y_{s,max} = \frac{1}{E_s I_s}\left[\frac{F L_s^3}{3}\right] + \frac{1}{E_c I_c}\left[F L_{cs} L_c L_s - \frac{F L_c^2 L_s}{2} + \frac{F L_{cs} L_c^2}{2} - \frac{F L_c^3}{6}\right], \quad (2)$$

and the strain (ε) at the location of the strain gauges ($x_C = L_C/2$) is given by **Equation 3**—

$$\varepsilon = \frac{F\left(L_{cs} - \frac{L_c}{2}\right)h_c}{2 E_c I_c}. \quad (3)$$

Equations 1 to **3** were used to arrive at a range of diameters whose force deflection characteristics were consistent with those obtained in our shoulder displacement and force measurements obtained as part of study aim 2 (see "Study Aim 2: Quantification of Shoulder Movement and Force Generation" section). Within the range of steel rod diameters, there were further limits on how stiff or flexible the rods could be. The upper limit in this regard would be a rod so stiff that shoulder movement would cause movement of the socket on the torso instead of bending of the rod. The lower limit would be a rod so flexible that that shoulder movement would not produce a signal of sufficient strength (measured by the strain gauges on the cantilever section) to be used for control. For our experiment, we selected two standard diameter rods that provided stiffnesses toward the extremes of this flexibility range and provided noticeably different sensations of resistance to movement. The first steel rod (2.36 mm diameter) provided just noticeable resistive feedback to shoulder motion. Its bending stiffness was approximately 4 N/cm. The second steel rod (3.04 mm diameter, bending stiffness approximately 11 N/cm) provided resistive feedback to shoulder motion that was very noticeable. **Equations 1** to **3** must be considered approximations. L_S, the distance between the steel rod's point of attachment to the aluminum base and the eyebolt, will vary slightly from one subject to the next. It will also change as the eyebolt moves along the rod when the subject moves his or her shoulder. These equations proved sufficiently accurate, though, to allow proper selection of the steel rods. **Table 1** lists mechanical properties for the two steel rod assemblies as well as the joystick assembly.

Study Aim 2: Quantify Shoulder Movement and Force Generation

Shoulder movement was measured using the apparatus shown in **Figure 4**. It consisted of a body socket (socket 2) on an adjustable stand, which was placed over the subject's right shoulder. The socket had openings at the location of the acromion process. The first opening was in the front of the body socket and was directed in the horizontal plane anterior to the subject's chest. The second opening was at the top of the body socket and was directed in the vertical plane above the subject's shoulder.

Table 1.
Physical characteristics of three assemblies tested.

Assembly	Material		Diameter (cm)		*E*, Young's Modulus (N/cm^2)		*I*, Moment of Inertia (cm^4)		Maximum Deflection at Eyebolt* (cm)	Strain at Strain Gauges† (cm/cm)
	Base	Rod	Base	Rod	Base	Rod	Base	Rod		
Joystick	Potentiometer	Nylon	NA	0.475	NA	NA	NA	NA	NA	NA
236 Steel Rod	Aluminum	Carbon Spring Steel	0.5	0.236	$6.90 \bullet 10^6$	$20 \bullet 10^6$	0.0052	0.00015	5.23	0.0021
304 Steel Rod	Aluminum	Carbon Spring Steel	0.5	0.304	$6.90 \bullet 10^6$	$20 \bullet 10^6$	0.0052	0.00042	2.09	0.0021

*$y_{s,max}$ ($x_s = L_s$, $F = 22$ N).
†$\varepsilon(x_c = L_c/2$, $F = 22$ N).
NA = not applicable.

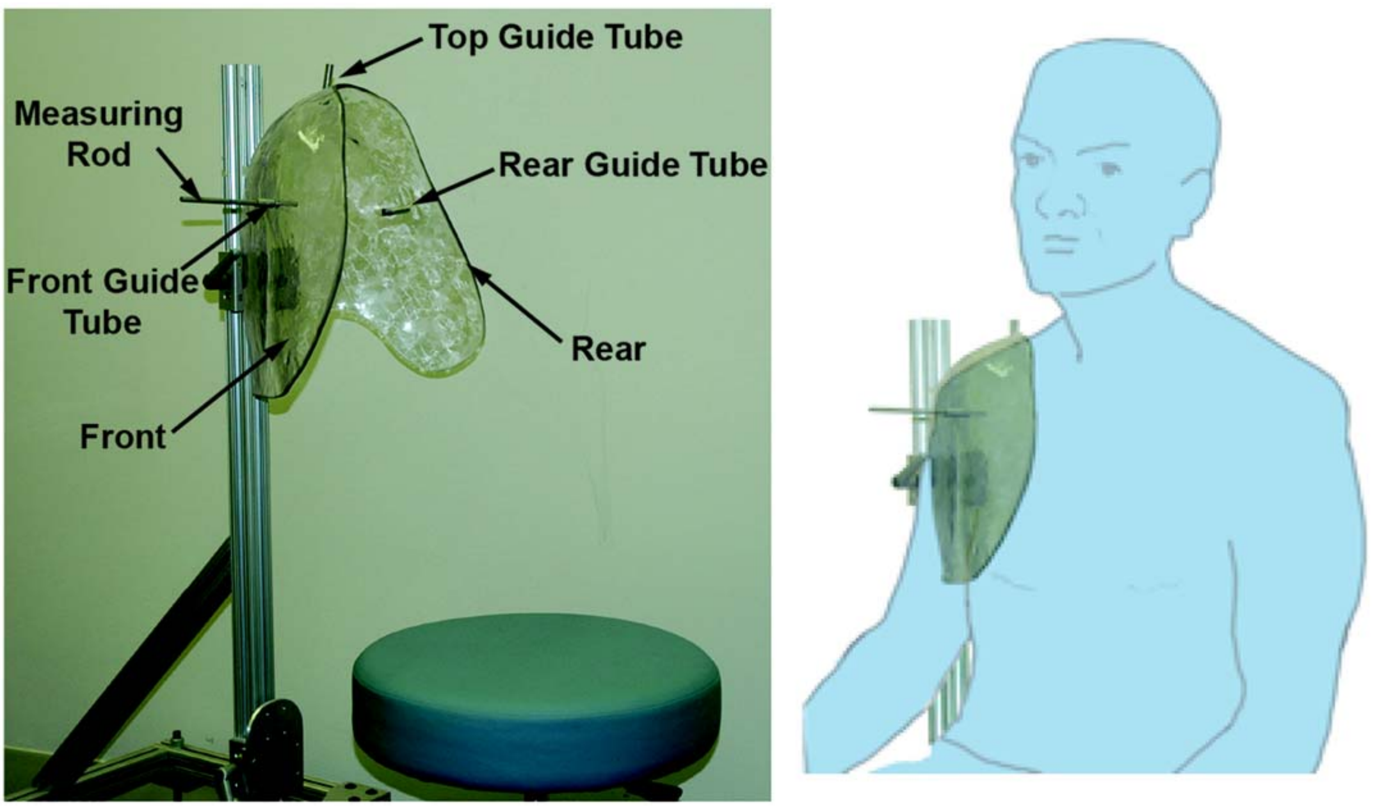

Figure 4.
Socket 2, used for measuring shoulder's range of motion. Subject's right shoulder is covered by socket as subject sits facing forward out of figure to reader's left. Top guide tube is lined up directly over acromion process. With shoulder in neutral position, steel measuring rod is passed through guide tube until it comes into contact with shoulder and its position at exit of guide tube is marked. Subject then moves his or her shoulder maximally against or away from rod, pushing it outward or allowing us to push it inward, and it is again marked. Distance between marks is measured with ruler and recorded. Rod is then moved sequentially to front guide and rear guide and procedure is repeated. This allows assessment of maximal elevation, depression, protraction, and retraction using top, front, and rear passages, respectively.

The final opening was in the back of the socket and pointed in the horizontal plane posterior to the subject's back. The three openings allowed us to quantify shoulder elevation, depression, protraction, and retraction. Motion in these four directions was quantified as follows. While each of 10 subjects sat with their shoulders in the neutral position, the socket was fitted over the subject's right shoulder. A steel rod was passed through one of the tubes, and the rod was placed in contact with the subject's acromion process. A mark was made on the rod at the point where it exited the tube. The subject was instructed to elevate, depress, protract, or retract his or her shoulder (depending on the opening through which the rod was placed) to a comfortable maximal displaced position, and a second mark was placed on the rod. Shoulder movement was recorded as the distance between the two marks as measured with a ruler. The metal rod was then placed in the next tube and the measurement technique was repeated, and again for the third tube. Five measurements were taken for each direction of motion (elevation, depression, protraction, and retraction). Five nondisabled (with all four limbs intact) men (ages 28–56 yr) and five nondisabled women (ages 26–61 yr) were studied.

Force measurements were taken using the same 10 test subjects. For these measurements, socket 2 was removed and a padded load cell was placed at the appropriate position and direction on or across from the acromion process. The subject was instructed to keep his or her shoulder in the same position and resist the force of the load cell while the load cell was pressed against the shoulder from above, the front, or the rear (force generated during shoulder depression could not be measured with this apparatus), and to indicate when the force applied by the load cell became uncomfortable to bear. At this point, the force applied by the load cell was recorded. Five measurements were taken in the direction of each of three possible shoulder displacements: elevation, protraction, and retraction.

Study Aim 3: Develop Method to Quantitatively Assess Prostheses Control

Fitts defined an index of difficulty (ID) for a pointing task as **Equation 4** [19]—

$$ID = log_2\left(\frac{D}{d} + 1\right), \qquad \textbf{(4)}$$

where D = the distance between the starting and ending points for a particular target configuration, and d = the diameter of a circle enclosing a region around the ending point. This procedure consists of measuring the time required to move a pointing device from a starting point to targets of varying size and distance (and thus difficulty). A plot of time (t) versus ID exhibits a linear relationship (**Figure 5**) of the form **Equation 5**—

$$t = m\ ID, \qquad \textbf{(5)}$$

where m (in seconds) is the slope of a straight line passing through the origin. The larger the value of m, the longer it takes to complete the pointing task for a given level of difficulty. Pointing devices with smaller values of m (i.e., shorter times to complete a given task for a given level of difficulty) are judged to perform better than those with higher values. Five subjects underwent computer-based testing where they were instructed to move a cursor on a visual display. The cursor was controlled via shoulder movement using one of the three assemblies described previously (see "Study Aim 1: Develop Shoulder Position Transducer" section). The display (**Figure 6**) consisted of 11 small circles of diameter (d) arranged around a larger

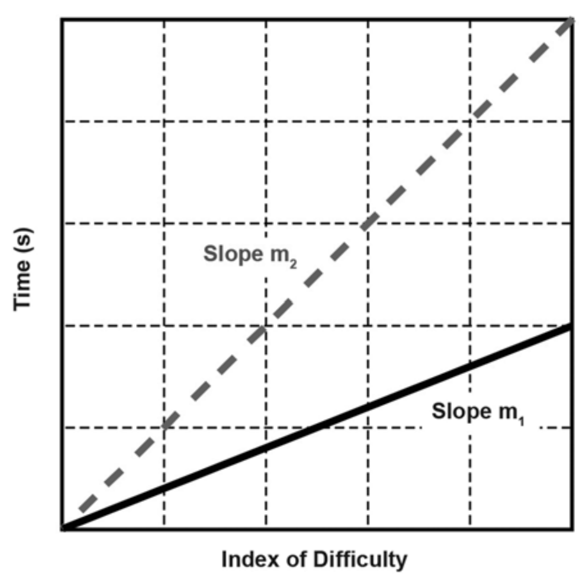

Figure 5.
For given index of difficulty, pointing devices exhibiting lesser slopes (m_1) complete given pointing task in less time than devices with greater slopes (m_2). Figure lacks units of measure on axes because slopes are used for illustrative purposes only.

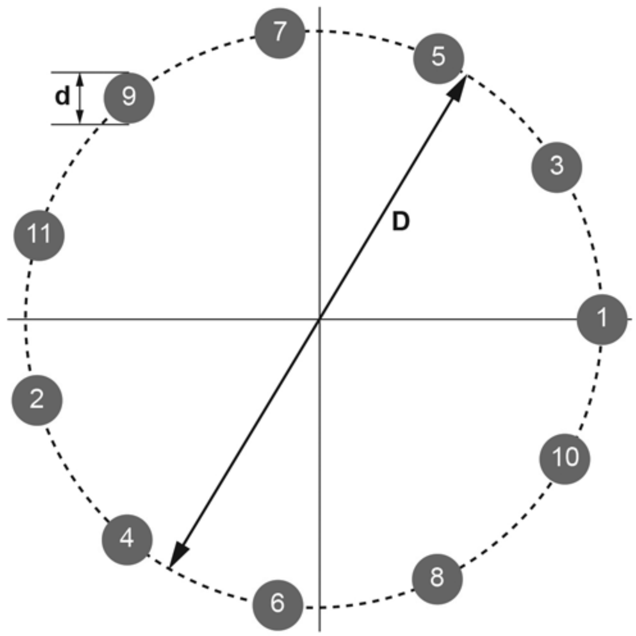

Figure 6.
Display used for Fitt's law-based evaluation protocol. Using shoulder control assemblies (**Figure 1**) mounted on socket 1 (**Figure 2**), subject moves cursor on display from target 1 to target 2 to target 3 and so on until returning to target 1 from target 11. Small and large diameters (*d* and *D*, respectively) are changed for each experimental condition, as identified in **Table 2**.

circle of diameter (*D*) [20]. Subjects were instructed to move the cursor from circle 1 to circle 2 to circle 3 and so on until returning to circle 1 from circle 11. A 20 in. liquid crystal display monitor was used for these experiments. The display's dimensions were 1,600 pixels wide by 1,200 pixels high. Pixel size was 0.264 mm in both the horizontal and vertical directions. Each subject underwent 16 trials in which they were presented with a different combination of large diameter (*D*) and small diameter (*d*) circles (and thus 16 different ID values). Because sequential targets are not diametrically opposite one another, the distance between them (D_{actual}) is slightly less than *D*. **Table 2** shows the different combinations of *D* (and D_{actual}) and *d* used. D_{actual} was used in the computation of the ID used in these experiments (**Equation 4**). The signals produced by the three assemblies were converted to cursor movements by MATLAB (MathWorks Inc; Natick, Massachusetts) and displayed on the computer monitor. Two different control schemes were used to control cursor movement with each of the three assemblies described previously: a position control scheme, in which cursor displacement was proportional to shoulder displacement, and a velocity control scheme, in which the speed of the cursor in the direction of shoulder displacement was proportional to shoulder displacement.

Each of the two control schemes was used to test each subject under the 16 conditions listed in **Table 2**, resulting in a total of 2 × 16 = 32 tests. Furthermore, each subject performed each of the 32 tests using the three assemblies described previously. Thus, each subject performed a total of 2 × 16 × 3 = 96 tests. The duration of a 16-test block was less than 30 min, thus the total duration of the experiment was approximately 3 h. Because it was necessary to refit the test socket with a different control assembly after each test block, the six 16-test blocks were not conducted contiguously but spaced over several days. Subjects rested at will between the tests within a block. No subject fatigue was reported (subjects were asked to rank their fatigue subjectively along a perceived exertion scale of 1–5), and none was observed. Subjects were tested with the different assembly-control scheme combinations in differing order to avoid learning effects.

Five nondisabled men and women with normal vision (corrected or uncorrected) were tested (4 of the 5 also participated in the previous shoulder movement and force measurements.) During testing, the subjects wore the body socket (socket 1) outfitted with one of the three shoulder control assemblies (**Table 1**) and stood facing a computer monitor. The time to move between each pair of small circles was recorded for each of the 11 paths comprising a test condition. Upon donning socket 1 and prior to the first cursor control test, each subject was asked to displace his or her shoulder to a comfortable maximum elevation, depression, protraction, and retraction, and the directional gains were adjusted so that the maximal displacement in each direction produced a signal change of 3 V. This allowed us to account for the effects of shifts in socket position from one donning to the next, as well as electrical differences in the control assemblies, so that performance differences due to differing levels of force feedback could be isolated and measured.

Statistical Methods

A linear mixed-effects model was used to assess the effect of the different assemblies and control schemes on the time to complete the pointing task over different IDs. The model included fixed-effect terms for assembly, control scheme, ID, assembly-by-time, control scheme-by-

Table 2.
Target characteristics used in 16 conditions.

Condition	*D*	D_{actual}		*d*		ID
	Pixels	Pixels	Millimeters	Pixels	Millimeters	
1	63	62.4	16.5	8	2.1	3.14
2	125	123.7	32.7	8	2.1	4.04
3	250	247.5	65.4	8	2.1	5.00
4	500	494.9	130.9	8	2.1	5.97
5	63	62.4	16.5	16	4.2	2.29
6	125	123.7	32.7	16	4.2	3.13
7	250	247.5	65.4	16	4.2	4.04
8	500	494.9	130.9	16	4.2	5.00
9	63	62.4	16.5	31	8.2	1.59
10	125	123.7	32.7	31	8.2	2.32
11	250	247.5	65.4	31	8.2	3.17
12	500	494.9	130.9	31	8.2	4.08
13	63	62.4	16.5	63	16.7	0.99
14	125	123.7	32.7	63	16.7	1.57
15	250	247.5	65.4	63	16.7	2.30
16	500	494.9	130.9	63	16.7	3.15

Note: *D* represents diameter of larger circle (**Figure 6**), and D_{actual} represents exact distance between sequential targets, which are not diametrically opposite one another. D_{actual} was used to compute ID. *d* represents diameter of smaller circle.
ID = index of difficulty.

time, and assembly-by-control scheme-by-ID and the random effect for the intercept and the slope at subject level.

RESULTS

Quantification of Shoulder Movement and Force Generation

Displacement and force measurements (**Table 3**) using socket 2 (**Figure 4**) showed that men and women exhibited similar movement range (3.2 cm average) and force generation (24 N average). The hypotheses that range of motion in each of the four directions differed between men and women were rejected: $0.64 < p < 0.90$; and the hypotheses that force generation differed between sexes were rejected: $0.10 < p < 0.84$.

Evaluation of Shoulder Position Transducers by Fitts' Law

Five subjects (4 who participated in study aim 2 and 1 who did not) were tested to assess control performance using our evaluation protocol adaptation of Fitts' law, the results of which are summarized in **Figure 7** and detailed in **Table 4**. Resistive feedback provided by the steel rod assemblies improved results obtained from the position control scheme but not the velocity control scheme. The position control scheme for the 236 steel rod (m = 0.26 s) was better ($p < 0.001$) than the position control scheme for the joystick (m = 0.49 s), which offered no resistive feedback (**Table 4**, "Joystick vs 236 Steel Rod"). Similarly, the position control scheme for the 304 steel rod (0.34 s) was better ($p < 0.01$) than the position control scheme for the joystick (0.49 s, "Joystick vs 304 Steel Rod, Position").

Resistive feedback did not improve the velocity control scheme: "Joystick vs 236 Steel Rod, Velocity" (0.39 s vs 0.35 s, $p < 0.44$) and "Joystick vs 304 Steel Rod, Velocity" (0.39 s vs 0.34 s, $p < 0.34$). There was a trend suggesting that in the absence of resistive feedback, the velocity control scheme is better than the position control scheme: "Joystick, Velocity" (0.39 s) versus "Joystick, Position" (0.49 s) ($p < 0.08$). None of the y-intercepts were significantly different from zero for any analysis except the joystick position control scheme (y-intercept = –0.37 s, standard error [SE] = 0.11, $p < 0.001$).

Our results suggest that a lower level of resistive feedback makes a position control scheme better than a velocity control scheme, and higher levels of resistive feedback defeats the improvement in the position control

Table 3.
Displacement and forces (mean ± standard error) exerted at acromion process.

Displacement (cm)	Male	Female	Overall
Elevation	4.0 ± 0.5	4.4 ± 0.5	4.2 ± 0.3
Protraction	4.1 ± 0.5	3.3 ± 0.6	3.7 ± 0.4
Retraction	3.0 ± 0.3	2.5 ± 0.5	2.8 ± 0.3
Depression	2.1 ± 0.3	2.3 ± 0.4	2.2 ± 0.3
Force (N)	**Male**	**Female**	**Overall**
Elevation	23.9 ± 3.4	27.6 ± 2.0	25.7 ± 2.0
Protraction	21.9 ± 3.5	21.1 ± 1.1	21.5 ± 1.7
Retraction	22.5 ± 2.6	27.9 ± 2.3	25.2 ± 1.9

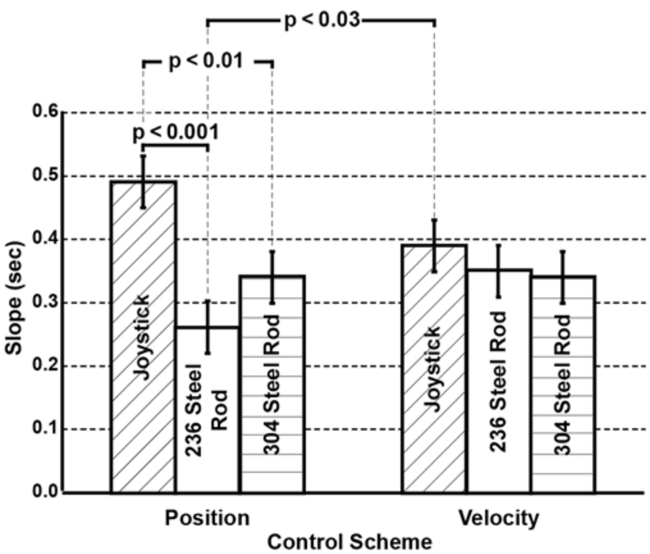

Figure 7.
Between-assembly performance comparisons. Lower values of slope indicate superior performance. Error bars are ±1 standard error.

scheme. The 236 steel rod position control scheme was better than the joystick velocity control scheme (0.26 vs 0.39 s, difference = –0.013, SE = 0.05, $p < 0.03$; comparison not shown in **Table 4**). The superiority of the position control scheme was not seen for the 304 steel rod, which offered greater resistance than the 236 steel rod ("304 Steel Rod, Position": 0.34 s, "Joystick, Velocity": 0.39 s, difference = –0.05, SE = 0.06, $p < 0.38$; comparison not shown in **Table 4**). Additional support for the supposition that low-level resistive feedback makes a position control scheme better than a velocity control scheme comes from the observations that there was a trend for the position control scheme to be better than the velocity control scheme ("236 Steel Rod, Position": 0.26 s versus "236 Steel Rod, Velocity": 0.35 s, $p < 0.10$). But a difference between position and velocity was not seen in the setting of the higher resistance afforded by the 304 steel rod ("304 Steel Rod, Position": 0.34 s, "304 Steel Rod, Velocity": 0.34 s, $p < 0.94$). There was no evidence that once resistive feedback was applied, the *degree* of resistance affected performance under the velocity control scheme ("236 Steel Rod, Velocity": 0.35 s, "304 Steel Rod, Velocity": 0.34 s, $p < 0.86$).

DISCUSSION

We developed a 2-DOF shoulder position transducer that translates shoulder protraction-retraction and elevation-depression into signals that can be used to control the powered humerus of advanced upper-limb prostheses that are currently under development, while at the same time providing proprioceptive and tactile feedback to the shoulder. To allow us to evaluate the transducer's performance, we developed an evaluation protocol based on Fitts' law. An evaluation procedure such as the one described here is generally applicable to any prosthetic limb control mechanism.

We found that both levels of resistance (236 and 304 steel rods) improved performance (lower slopes, **Equation 5**) under the position control scheme ($p < 0.001$ and $p < 0.01$, respectively) compared with no resistance (joystick), but we found no evidence that resistance improved performance under the velocity control scheme ($p < 0.44$ and $p < 0.34$, respectively). In the absence of resistance, there was a trend for the velocity control scheme to perform better than the position control scheme ($p < 0.08$); in the presence of low-level resistance, there was a trend for the position control scheme to perform better than the

Table 4.
Comparison of slopes and intercepts obtained from three assemblies using position and velocity control schemes.

Comparison	Joystick (No Resistance)			236 Steel Rod (Low Resistance)			304 Steel Rod (High Resistance)		
	Position	Velocity	Difference	Position	Velocity	Difference	Position	Velocity	Difference
Within-Assembly Comparisons									
Position vs Velocity									
Slope	0.49	0.39	0.09	0.26	0.35	–0.09	0.34	0.34	0.00
SE	0.04	0.04	0.05	0.04	0.04	0.05	0.04	0.04	0.05
p-Value	—	—	0.08	—	—	0.10	—	—	0.94
Between-Assembly Comparisons									
Joystick vs 236 Steel Rod									
Position									
Slope	0.49	—	—	0.26	—	—	—	—	–0.22
SE	0.04	—	—	0.04	—	—	—	—	0.05
p-Value	—	—	—	—	—	—	—	—	0.001
Velocity									
Slope	—	0.39	—	—	0.35	—	—	—	–0.04
SE	—	0.04	—	—	0.04	—	—	—	0.05
p-Value	—	—	—	—	—	—	—	—	0.44
Joystick vs 304 Steel Rod									
Position									
Slope	0.49	—	—	—	—	—	0.34	—	–0.15
SE	0.04	—	—	—	—	—	0.04	—	0.05
p-Value	—	—	—	—	—	—	—	—	0.01
Velocity									
Slope	—	0.39	—	—	—	—	—	0.34	–0.05
SE	—	0.04	—	—	—	—	—	0.04	0.05
p-Value	—	—	—	—	—	—	—	—	0.34
236 Steel Rod vs 304 Steel Rod									
Position									
Slope	—	—	—	0.26	—	—	0.34	—	–0.07
SE	—	—	—	0.04	—	—	0.04	—	0.05
p-Value	—	—	—	—	—	—	—	—	0.16
Velocity									
Slope	—	—	—	—	0.35	—	—	0.34	0.01
SE	—	—	—	—	0.04	—	—	0.04	0.05
p-Value	—	—	—	—	—	—	—	—	0.86
***y*-Intercept**									
Value	–0.37	–0.13	—	–0.05	–0.11	—	–0.08	0.00	—
SE	0.11	0.11	—	0.11	0.11	—	0.11	0.11	—
p-Value	0.001	0.22	—	0.68	0.31	—	0.50	0.97	—

SE = standard error.

velocity control scheme ($p < 0.10$), but in the presence of high-level resistance, there was no difference between the position and velocity control schemes ($p < 0.94$).

Overall, of the six assembly control schemes tested, the best (the one with the smallest slope) was the 236 steel rod under the position control scheme. Of the two assemblies that provide resistive feedback, the 236 steel rod provided the lesser feedback. For this assembly, we also found that the position control scheme (where cursor displacement is proportional to shoulder displacement) performed slightly better than the velocity control scheme (where cursor velocity is proportional to shoulder displacement). Although the slopes were smaller for the steel rod assemblies than for the joystick assembly, it is important to note that statistically significant differences were seen only when comparing the position control scheme for the 236 and 304 steel rods with the position control scheme for the joystick and the position control scheme for the 236 steel rod with the velocity control scheme for the joystick.

We believe that the resistance to motion offered by the steel rod assemblies under the position control scheme is responsible for their superior performance compared with that of the joystick assembly under the position control scheme, which offered no resistive feedback. By introducing resistance to shoulder movement, we can provide the prosthesis user with a better "feel" for its location in space, which can be used to improve control of the prosthesis. Though our results indicate that resistance feedback to position is better than no resistance, the lack of significant differences between the 236 and 304 steel rods is consistent with a hypothesis that the shoulder is insensitive to the degree of resistance in the range provided by our two rods (22–28 N), but we cannot rule out the hypothesis that our inability to find a significant difference between the two steel rod assemblies represents a type II error (a false negative).

Our results also suggested that the position control scheme was better than the velocity control scheme in the presence of low-level resistance (although this difference was not statistically significant). Of note, three subjects who were asked to give a subjective evaluation of the control schemes indicated a preference for the velocity control scheme. They found that while they could move the cursor from the starting position to the vicinity of the target circle more quickly with the position control scheme, locating and holding the cursor within the target (which required holding the acromion process at a precise point in three-dimensional space, away from its rest position) proved difficult because the shoulder was subject to tremors that prevented the cursor from settling within the target. The shoulder's task is fundamentally different under the velocity control scheme. Here, the subject "pushes" the cursor across the screen with brief shoulder thrusts in the desired direction. Large, fast movements are accomplished with large thrusts and short precise movements by small thrusts. Under the velocity control scheme, if a subject thrusts the shoulder forward and then returns toward the neutral position, the cursor slows to a stop at its current position. This allows the subject to briefly "rest and regroup" (any delays were extremely brief and unnoticeable when observing the subjects perform the movement task). In contrast, under the position control scheme, the cursor returns to the starting position if the subject returns his or her shoulder toward neutral. Under this control scheme, the shoulder is constantly at work and subject to fatigue and tremors. Shoulder tremors were not encountered under the velocity control scheme because the subject was able to "nudge" the cursor into the target with short thrusts, keeping the shoulder alternately at or close to the neutral position. (This, strictly speaking, violates Fitts' law's basic assumption that subjects move toward a target with maximum velocity. We observed, however, that discrete thrusts of the shoulder were virtually unnoticeable, especially once subjects were acclimated to the task, and believe that their shoulder movements were a sufficiently close approximation to Fitts' law's assumption that use of the method was justified.) In summary, course movement over large distances is faster with the position control scheme, while precise positioning of the cursor is faster and easier with the velocity control scheme. Thus, the position control scheme is better than the velocity control scheme when making initial large movements where speed is more important, but it partially loses this advantage at the end of the movement where precision is paramount. When no resistance was present, the advantage appeared to disappear entirely (see next), and performance under the velocity control scheme was better ($p < 0.08$).

Shoulder tremors also help to explain the fact that resistance improved performance under the position control scheme but not the velocity control scheme. We believe that the steel rod assemblies helped to damp the shoulder tremors that occurred under the position control scheme, enabling the subject to settle the cursor within the target more quickly than without resistance. As noted previously, tremors, if present, did not significantly affect performance of the velocity control scheme. Once introduced, increasing the resistance supplied by the 306 steel rod had little, if any, effect.

We noted the presence of a nonzero *y*-intercept (**Equation 5**) when using the joystick (no resistance to shoulder motion) with the position control scheme, but at no other time. A nonzero *y*-intercept indicates that the pointing device (the cursor on the computer screen) did not move continuously toward the target from start to finish. The cursor either stopped midcourse for a period of time or moved backward or orthogonally with respect to the direction toward the target. This could arise when significant "noise" is associated with the movement. In our case, this noise would be the result of the shoulder tremors noted previously, which would have been most prevalent in the absence of resistive feedback, i.e., when the joystick was employed.

We cannot rule out the possibility that the gains used in the two control schemes contributed to the lack of significant differences between the velocity and position control schemes. Due to the constraints of our pilot study, gains were set such that maximal shoulder displacement in each direction produced a signal change of 3 V. This strategy may not have been optimal. A more comprehensive assessment would involve first varying the gain for each assembly/control scheme and subject, with the goal of finding the gain for each assembly/control scheme that gave optimal performance (using our Fitts' law-based evaluation protocol) and then comparing the two optimized control schemes to identify which was superior. This is planned for a future study.

CONCLUSIONS

We developed three prototype 2-DOF prosthetic shoulder controllers, along with a method to evaluate and compare their performance using position and velocity control schemes. Steel rod assemblies (which incorporate feedback) utilizing a position control scheme performed better than a joystick assembly (in which feedback is absent) utilizing either a position or a velocity control scheme. The next step will be to use the controller to control a prosthetic arm where it and the evaluation protocol can be tested and validated. A particularly important aspect of this evaluation will be to compare the evaluation protocol's results with the more subjective subject assessments of control scheme/assembly performance. In order to realize the full benefits of feedback, the controller characteristics should match the dynamic characteristics of the controlled prosthetic limb.

The shoulder-operated controller developed here is not limited to the control of a prosthetic humerus but can be applied in other applications as well. It can be used to control two DOFs for any prosthesis and can also be used in a more general 4-DOF control scheme by sequentially controlling two DOFs at a time. It can also be used in applications unrelated to prosthetics, e.g., to assist people with paralysis in controlling powered wheelchairs [17] as well as other types of machines. An evaluation protocol based on Fitts' law such as the one we developed in this study has general applicability for researchers as well as practitioners. Researchers can employ it to compare different prosthesis designs and control schemes, while practitioners could find the protocol useful in evaluating and training people with amputation in the use of such prostheses.

ACKNOWLEDGMENTS

Author Contributions:
Study design: J. E. Barton.
Acquisition of data: J. E. Barton.
Interpretation of data: J. E. Barton.
Drafting of manuscript: J. E. Barton, J. D. Sorkin.
Statistical analysis: J. E. Barton, J. D. Sorkin.

Financial Disclosures: The authors have declared that no competing interests exist.

Funding/Support: This material was based on work supported in part by the Geriatrics Research, Education, and Clinical Center, Baltimore Department of Veterans Affairs Medical Center; the Claude D. Pepper Older Americans Independence Center (grant NIA P30 AG028747 07); and the Mid-Atlantic Nutrition Obesity Research Center (grant P30-DK072488–07).

Additional Contributions: Dr. Barton is now with the Departments of Neurology and Physical Therapy and Rehabilitation Science, University of Maryland School of Medicine, Baltimore, Maryland, and the Maryland Exercise and Robotics Center of Excellence, Rehabilitation Research and Development Service, Department of Veterans Affairs, Baltimore, Maryland.

Institutional Review: All of the subjects who participated in the study gave informed consent according to the guidelines of the Rehabilitation Institute of Chicago and Northwestern University Institutional Review Boards.

Participant Follow-Up: The authors do not plan to notify the study subjects of the publication of this article because of a lack of contact information.

REFERENCES

1. Kyberd PJ, Poulton A, Gow D, Sandsö L, Jones B. The ToMPAW modular prosthesis—A platform for research in upper limb prosthetics. J Prosthet Orthot. 2007;19(1):15–21. http://dx.doi.org/10.1097/JPO.0b013e31802d46f8
2. Burger H, Marincek C. Upper limb prosthetic use in Slovenia. Prosthet Orthot Int. 1994;18(1):25–33. [PMID:8084746]
3. Dudkiewicz I, Gabrielov R, Seiv-Ner I, Zelig G, Heim M. Evaluation of prosthetic usage in upper limb amputees. Disabil Rehabil. 2004;26(1):60–63. [PMID:14660200] http://dx.doi.org/10.1080/09638280410001645094

4. Datta D, Selvarajah K, Davey N. Functional outcome of patients with proximal upper limb deficiency—acquired and congenital. Clin Rehabil. 2004;18(2):172–77. [PMID:15053126] http://dx.doi.org/10.1191/0269215504cr716oa
5. Kejlaa GH. Consumer concerns and the functional value of prostheses to upper limb amputees. Prosthet Orthot Int. 1993;17(3):157–63. [PMID:8134275]
6. Milstein SG, Bain DA, Hunter GA. A review of employment patterns of industrial amputees—Factors influencing rehabilitation. Prosthet Orthot Int. 1985;2:69–78.
7. Jones LE, Davidson JH. Save that arm: A study of problems in the remaining arm of unilateral upper limb amputees. Prosthet Orthot Int. 1999;23(1):55–58. [PMID:10355644]
8. Klopsteg PE; National Academy of Sciences, National Research Council, Advisory Committee on Artificial Limbs. Human limbs and their substitutes. New York (NY): McGraw-Hill; 1954.
9. Nightingale J, Swain I. Adaptive control of an artificial arm. Proceedings of the 6th International Symposium on External Control of Human Extremities; 1978 Aug 28–Sep 1; Dubrovnik, Yugoslavia.
10. Swain ID, Nightingale JM. An adaptive control system for a complete hand/arm prosthesis. J Biomed Eng. 1980;2(3): 163–66. [PMID:7412244] http://dx.doi.org/10.1016/0141-5425(80)90142-9
11. Gow DJ, Douglas W, Geggie C, Monteith E, Stewart D. The development of the Edinburgh modular arm system. Proc Inst Mech Eng H. 2001;215(3):291–98. [PMID:11436272] http://dx.doi.org/10.1243/0954411011535885
12. Troncossi M, Gruppioni E, Chiossi M, Cutti A, Davalli A, Parenti-Castelli V. A novel electromechanical shoulder articulation for upper-limb prostheses: From the design to the first clinical application. J Prosthet Orthot. 2009;21(2): 79–90. http://dx.doi.org/10.1097/JPO.0b013e31819f6aed
13. DARPA Biological Technologies Office [Internet]. Revolutionizing prosthetics. Arlington (VA): DARPA; 2011. Available from: http://www.darpa.mil/Our_Work/BTO/Programs/Revolutionizing_Prosthetics.aspx
14. Kuiken T. Targeted reinnervation for improved prosthetic function. Phys Med Rehabil Clin N Am. 2006;17(1):1–13. [PMID:16517341] http://dx.doi.org/10.1016/j.pmr.2005.10.001
15. Englehart J, Hudgins B, Chan AD. Continuous multifunction myoelectric control using pattern recognition. Technol Disabil. 2003;15:95–103.
16. Weir RF, Troyk PR, DeMichele G, Kerns D. Technical details of the implantable myoelectric sensor (IMES) system for multifunction prosthesis control. Proceedings of the 27th Annual International Conference of the Engineering in Medicine and Biology Society; 2006 Jan 17–18; Shanghai, China. p. 7337–40.
17. Bayer DM, Lord RH, Swanker JW, Mortimer JT. A two-axis shoulder position transducer for control of orthotic/prosthetic devices. IEEE Trans Ind Electron. 1972;IECI-19(2):61–64. http://dx.doi.org/10.1109/TIECI.1972.351107
18. Lipschutz RD, Lock B, Sensinger J, Schultz AE, Kuiken TA. Use of two-axis joystick for control of externally powered shoulder disarticulation prostheses. J Rehabil Res Dev. 2011;48(6):661–67. [PMID:21938653] http://dx.doi.org/10.1682/JRRD.2010.04.0072
19. Fitts PM. The information capacity of the human motor system in controlling the amplitude of movement. J Exp Psychol. 1954;47(6):381–91. [PMID:13174710] http://dx.doi.org/10.1037/h0055392
20. Soukoreff RW, MacKenzie IS. Towards a standard for pointing device evaluation, perspectives on 27 years of Fitts' law research in HCI. Int J Hum Comput Stud. 2004; 61(6):751–89. http://dx.doi.org/10.1016/j.ijhcs.2004.09.001
21. Park J, Bei W, Kim H, Park S. EMG—Force correlation considering Fitts' law. Proceedings of the IEEE International Conference on Multisensor Fusion and Integration for Intelligent Systems; 2008 Aug 20–22; Seoul, Korea. p. 644–49.
22. Williams MR, Kirsch RF. Evaluation of head orientation and neck muscle EMG signals as command inputs to a human-computer interface for individuals with high tetraplegia. IEEE Trans Neural Syst Rehabil Eng. 2008;16(5): 485–96. [PMID:18990652] http://dx.doi.org/10.1109/TNSRE.2008.2006216
23. Choi C, Micera S, Carpaneto J, Kim J. Development and quantitative performance evaluation of a noninvasive EMG computer interface. IEEE Trans Biomed Eng. 2009;56(1): 188–91. [PMID:19224732] http://dx.doi.org/10.1109/TBME.2008.2005950
24. Scheme EJ, Englehart KB. Validation of a selective ensemble-based classification scheme for myoelectric control using a three-dimensional Fitts' Law test. IEEE Trans Neural Syst Rehabil Eng. 2013;21(4):616–23. [PMID:23193252] http://dx.doi.org/10.1109/TNSRE.2012.2226189
25. Scheme EJ, Hudgins BS, Englehart KB. Confidence-based rejection for improved pattern recognition myoelectric control. IEEE Trans Biomed Eng. 2013;60(6):1563–70. [PMID:23322756] http://dx.doi.org/10.1109/TBME.2013.2238939
26. Scheme E, Lock B, Hargrove L, Hill W, Kuruganti U, Englehart K. Motion normalized proportional control for improved pattern recognition based myoelectric control. IEEE Trans Neural Syst Rehabil Eng. 2013 Mar 7. Epub ahead of print. [PMID:23475378]

27. Young WC, Budynas RG, Roark RJ. Roark's formulas for stress and strain. 7th ed. New York (NY): McGraw-Hill; 2002.

Submitted for publication May 28, 2013. Accepted in revised form December 24, 2013.

This article and any supplementary material should be cited as follows:
Barton JE, Sorkin JD. Design and evaluation of prosthetic shoulder controller. J Rehabil Res Dev. 2014;51(5): 711–26.
http://dx.doi.org/10.1682/JRRD.2013.05.0120

ResearcherID/ORCID: Joseph E. Barton, PhD: G-6399-2014; John D. Sorkin, MD, PhD: C-1743-2013