Physics applied to post-stroke rehabilitation: June 15, 2011 interim report

Adam Blumenau, David O. Girardo, Ephedyn L. Lin, Sahit Mandala*, and Marko B Popovic
Worcester Polytechnic Institute, 100 Institute Road, Worcester, MA 01609-2280
*Massachusetts Academy of Math and Sciences at WPI, 85 Prescott Street, Worcester, MA 01605

Abstract

Imagine a world where orthotics are not simple passive supports for physically challenged people, but rather highly cooperative, smart devices. They are lightweight and simple to don and doff, respond to the user's intent and enable normal healthy limb like use. They can help users relearn natural movement pathways following stroke and injury, or provide exercise tailored to the user's specific disabilities.

A new generation of soft and active orthotics is proposed for a broad range of applications in physical therapy and rehabilitation. As part of the AIP SPS funded project, we began development of such orthopedic braces through physics based biomechanical simulation, human subject experiments, data analysis and experimentation with a biologically-inspired shoulder-arm model and a preliminary sensor network. A joint work with collaborators at the Harvard University shows that the proposed braces can be successfully actuated with biologically-realistic forces [1]. Furthermore, our recent results demonstrate that arm angular position can be accurately estimated with inexpensive, piezoelectric flex sensors embedded in the brace.

1. Introduction

Stroke is the leading cause of long-term disability in the United States, affecting over 750,000 people annually. Rehabilitation is the most effective method for restoring limb motor control after a serious stoke event. Standard rehabilitation methods require the dedicated attention of trained physical therapists to move the patients through a series of motion exercises to spur the regeneration of their neurophysiology and muscle control. This process is time consuming and expensive, requiring regular work with therapists to make any significant improvement.

Our advisor at Worcester Polytechnic Institute, Professor Marko B. Popovic leads this project with a long-term goal of introducing a new paradigm of soft, smart, actuated orthopedic braces for the post-stroke treatment. We propose an inexpensive and wearable upper body orthotics system that can be used at home to provide the same level of rehabilitation as the current standard of care in physical therapy.

Most previous actuated systems for upper body rehabilitation use expensive rigid exoskeletons or rigid link manipulators. Common problem with these devices is that small misalignments cannot be appropriately addressed causing user's discomfort. Soft devices, on the other hand, take advantage of natural anatomical structures, including joints and bones, to provide the device structure and determine the kinematic degrees of freedom (DOF).

Hence the long-term goal is to develop thin, compliant, force generating surface consisting of a number of muscle-like, series elastic actuators (SEA) with embedded sensor network. Brace will sense human movement dynamics and respond by generating appropriate assistive forces. Brace will automatically accustom across multiple users and it will automatically adapt to single user over time.

Towards the successful implementation of this long-term goal, we studied shoulder arm biomechanics via experiment and simulation, built a mechanical prototype of artificial shoulder arm platform, created sensor network consisting of flex sensors and accelerometer, and integrated all mentioned elements with commercially available shoulder stabilizing brace. Here we present a very important proof of concept that: (1) the active soft orthotic brace can be successfully actuated via biologically-realistic forces and torques and that (2) the proposed inexpensive sensor network embedded in the brace can successfully measure the large range of arm angles.

2. Physics based shoulder arm biomechanics and simulation

The proposed design was simulated to better understand how the design parameters impact the system performance [1]. A human arm model was constructed in order to calculate physical quantities such as moment due to gravity and to address cable attachment framework of single and double cable systems. The simplified three-segment arm model consists of the upper arm, forearm and hand. The arm segments' relative to body mass and the segments' center of mass locations relative to the arm length are modeled according to the average human [2],[3]. The arm model is customized to best match the anatomical properties of the subject of the experimental study based on the subject's weight, arm length and the upper arm proximal to the shoulder joint.

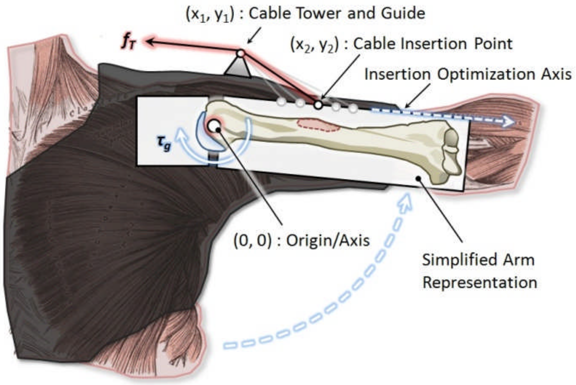


Figure 1: Simulation Model (from ref [1])

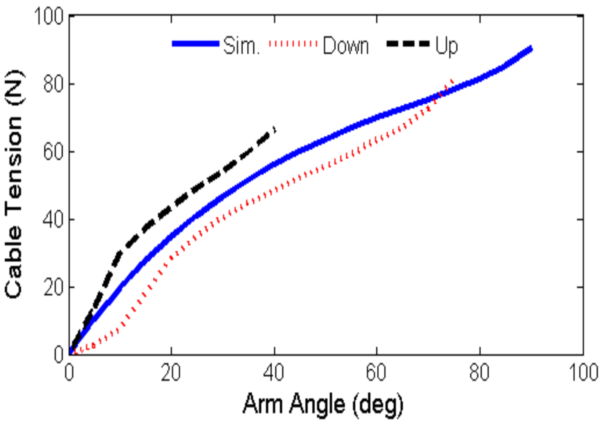


Figure 2: Abduction-adduction experiment (from ref [1])

The model gravity moment, , is obtained as function of the arm abduction/adduction angle and is the sum of the moments of individual segments. Each segment's lever arm is approximated by the horizontal distance between the arm's center of rotation and the segment's center of mass. The coordinate frame origin is located at the gleno-humeral joint and the shoulder tower and the upper arm cable insertion point are (x_1,y_1) and (x_2,y_2) , respectively; Fig.1. Assuming a static balance condition, arm motion confined within coronal plane, and neglecting friction between the cable and guide, the cable tension is

$$f_T = \frac{\sqrt{(x_1-x_2)^2+(y_1-y_2)^2}}{x_2y_1-y_2x_1}\tau_g .$$

This model is used to validate experimental results in [1]. During the experiment, the test subject was braced in the sitting position while another researcher actuated the cable system. This approach was taken to insure the safety of the subject during this initial evaluation phase of the project. As the arm was raised and lowered though a number of discrete static shoulder abduction-adduction elevation levels (~20 levels for each raising-lowering cycle), the position of the subject's torso, shoulder tower, and forearm were recorded using the EM trackers. The cable tension was recorded using a precision spring scale for each position. This research was approved by the Harvard University Institutional Review Board.

The results in Fig. 2 fit the simulation results very closely. The simulation predicts similar cable tensions to those found in the experiment, however without the hysteresis effects caused by the friction forces. The simulation matches the experimental results with an RMS error of 7.4 N.

As important proof of concept this experimental study demonstrated that shoulder-arm brace can be actuated with biologically realistic forces and that it performed accordingly to the original expectations while actuated with a single cable system.

3. Experimental apparatus

3.1. Biologically inspired shoulder-arm mechanical platform

The biologically inspired shoulder-arm mechanical platform, Fig. 3 and Fig 4, is designed to support large range of angles, forces, and torques as observed in biomechanical studies for the real human arm. This setup is intended to mitigate irregularities of the human anatomy over extended time, and allow uniform testing of our current sensor network and future actuation system. The shoulder-arm is constructed of laser cut acrylic and has three degrees of freedom in order to approximate the motions of a ball joint.

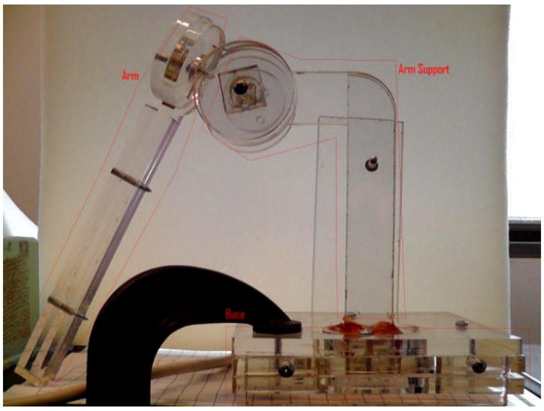


Figure 3: Side view, shoulder-arm platform

Figure 4: Top view, shoulder-arm platform

The arm is made of three main segments. The square base contains one degree of freedom and holds the arm vertical. The arm support (with the bend) contains a second degree of freedom. Off of this arm piece is the last longer arm bar that turns in a third degree of freedom. The front and back of the base also have two vertical pieces to simulate the chest. This plastic skeleton is then covered with foam to cushion it from large forces and to simulate the tissue compliance of a human arm. This entire structure is covered with a rubber brace, commercially available Sully shoulder stabilizer, which our measurement devices are attached to in order to record the angle and acceleration of the arm movements.

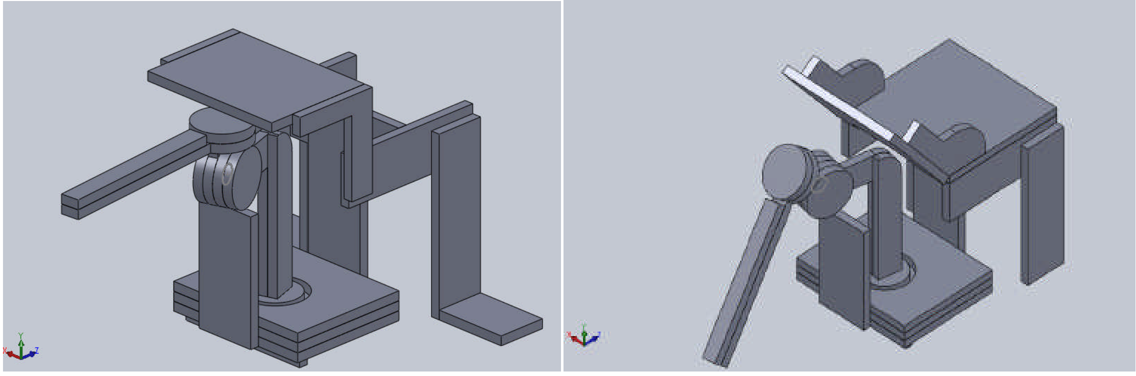


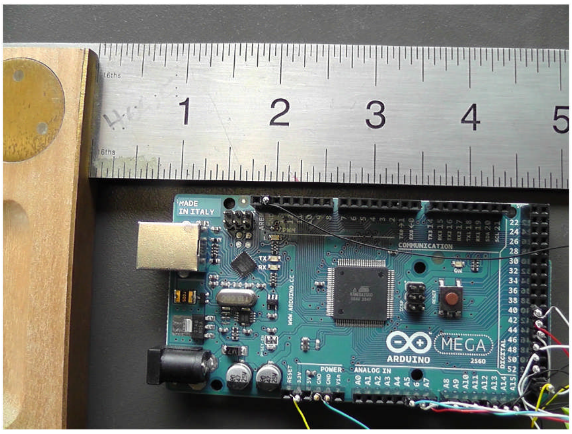
Figure 5: Computer-aided design of improved, larger-scale shoulder-arm model.

A second, larger shoulder-arm model, Fig. 5 is being built to address advanced system requirements.

3.2. The shoulder brace sensor network

The sensor network is composed of 6 flex sensors coupled with a 3-directional accelerometer embedded in a brace. The flex sensor, Fig 7, operate on a piezoelectric principle, responding to angular displacement with a variable resistance. The bend sensors are placed to give maximal variability and minimal degeneracy over the movement space with accelerometer at the end-effector to give relative orientation.

The data aquisition circuit is made of separate voltage dividers, each consisting of fixed resistors, and the 6 bend sensors, acting as variable resistors. A current is passed through the circuit and an analog-to-digital converter (ADC) is capable of taking voltage readings and producing a digital output. We used the Arduino Mega2560 microcontroller, Fig. 6, and its onboard, multi-channel ADC for rapid prototyping due to its low cost and time requirements. The Arudino also has accelerometer channels to support our accelerometer. The readings are processed in the microcontroller board and logged on the laptop via USB.



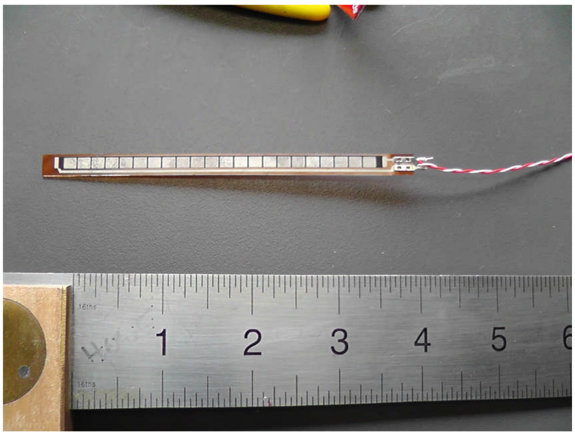


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Figure 6: Arduino Mega 2560 microcontroller.

Figure 7: Flex sensor

In addition to our sensor network, four of ``Flock of Birds" sensors, manufactured by Ascension Technology, at the Harvard School of Engineering and Applied Sciences' Biorobotics Laboratory, were used simultaneously to our bend sensors (connected via white cables in Fig. 8-9). Each miniBIRD sensor gives highly accurate readings for relative position and rotation in three dimensions. These sensors were used only as an absolute reference to calibrate our sensor network, but are incapable of quick sampling rates required for our eventual goal of real-time control.

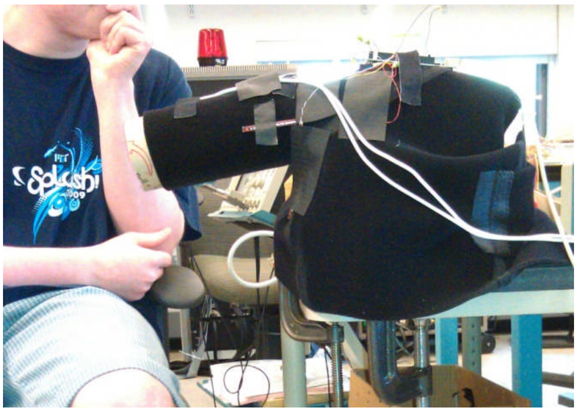


Figure 8: Side view, shoulder brace and sensors.

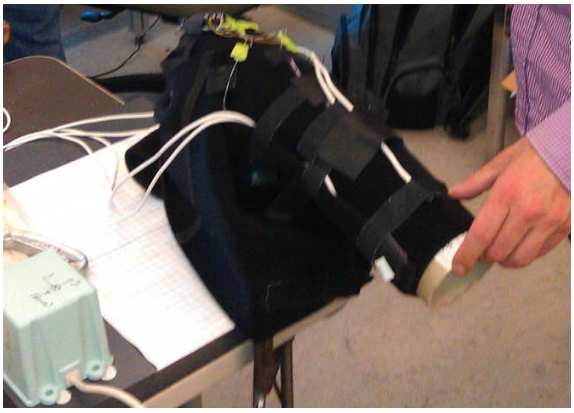


Figure 9: Side top view, shoulder brace and sensors.

4. The fist experiment with Flock of Birds sensors and shoulder brace sensor network

The initial experimentation consisted of simultaneous readings of our network and the Flock of Birds sensors on our mechanical arm model. An initial jolt was given to allow synchronization of the two systems during analysis. The arm model was moved left-right, up-down, diagonally, circularly, and randomly; each at varying speeds. This initial data is meant to give a set of 'training data' with which to build a functional map from ``sensor space" to ``angle space".

Our preliminary test comprised of using the flex sensor network alongside the Flock of Birds sensors to obtain a stream of data such that we could compare with the relative readings of the sensors for calibration. Furthermore, the test provided the opportunity to ensure that the set up, from the sensor positions to the circuit to the model arm, was robust and that anomalies could be found. After this test, with all major problems that arose solved, we will progress onto a real human arm data collection.

The test was run on our first shoulder-arm model platform prototype. Of the 6 flex sensors, 5 were used to collect data while 1 was used as a control experiment. The 5 flex sensors were positioned around the mock joint tangentially, placed equidistant around it in a stretched out initial position. The Flock of Birds sensors were placed such that a pair of them was linearly positioned behind each other. The two pairs were positioned one to each limb, where each pair could define a linear disposition of each limb, such that one could determine the spatial position of the arm relative to each other using these lines.

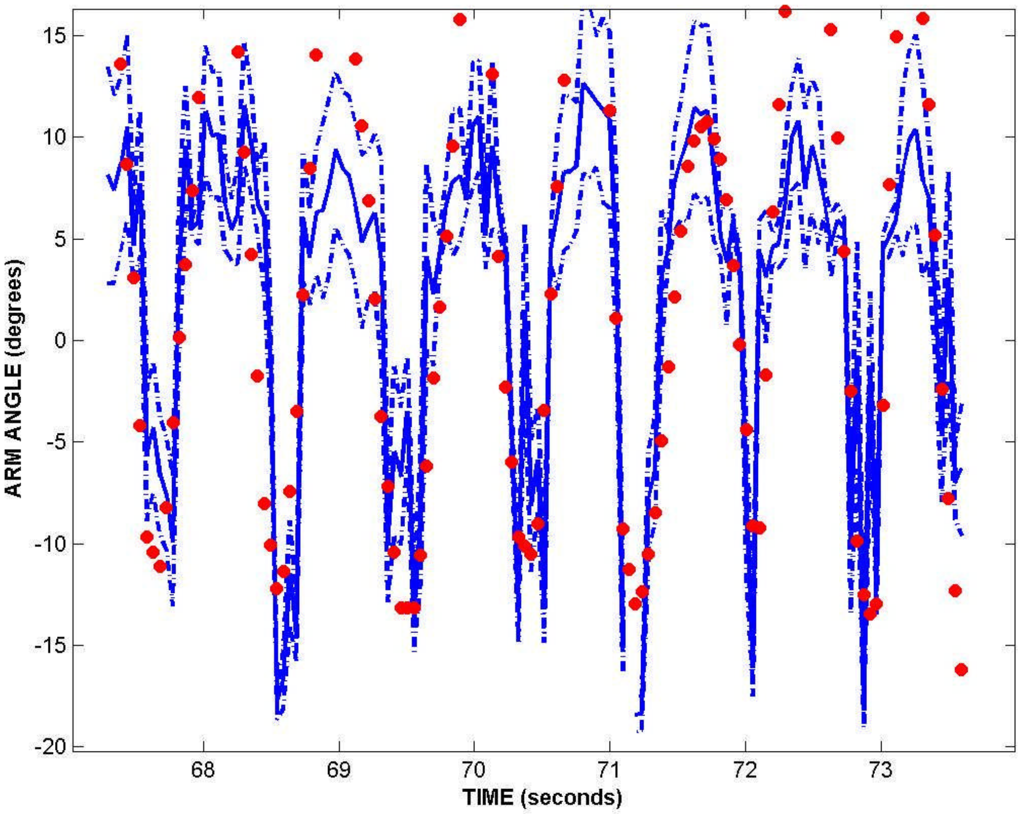


Figure 10: The arm angles in respect with the horizontal plane: as obtained from the accurate ~$8500 Flock of Birds sensors, red dots, and mean value, solid blue line, plus minus one standard deviation, dashed-dotted blue lines, as obtained from the inexpensive ~$60 flex sensors network.

This test was carried out for approximately 90 seconds. Data from both the Flock of Birds sensors the flex sensor network were streamed and logged simultaneously throughout the test. The model arm was manually bent through arbitrary motions, from circular arcs to instantaneous up-and-down motions. The data was yielded in the form of x,y, z position and quaternions for the Flock of Birds, which is eventually translated into arm angles, and voltage drops by the flex sensors, The test yielded usable data for the model arm; and the shoulder-arm model and flex sensor network behaved according to specifications.

5. Data analysis and results

Out of total of 90 seconds of experimental data, during which time the arm was moved through large range of angles, the first 60 seconds were used as a training data set for machine learning. The obtained lookup table was then used at later times to match, via linear interpolation, the flex sensors data with arm angles as obtained from the Flock of Birds sensor network.

The resulting arm angles with respect to the horizontal plane, i.e. plane orthogonal to the gravity vector, show excellent agreement between the data from the shoulder-brace flex sensor network and data from the Flock of Birds sensor network, which have been calibrated for high accuracy; Fig 10. Hence, we attained excellent agreement between the first prototypes of our sensor network built from $63.44 of inexpensive flex sensors purchased using our AIP SPS funds, and the $8,495 Flock of Birds setup of 6 DOF sensors employing pulsed DC magnetic technology. These are very promising results and proof of concept of our inexpensive and highly robust sensor network approach.

6. Future work: Biologically inspired control, novel hardware and experimentations

We also collected data on human arm trajectory in an experiment were subject was asked to point toward moving target. In this experiment the 3 EM Flock of Birds sensors were positioned on the subject's shoulder, elbow and wrist joints and one sensor was a moving target. The target was moved by another researcher. We plan to analyze this data and deduce the best set of parameters for the biologically inspired brace and arm movement control. We also plan to analyze data collected earlier at the Spaulding Rehabilitation Hospital and try to deduce the optimal set of dynamical primitives via principal component analysis. Good physical model will be critical for this task.

Substitutes are being considered for the materials used in our first prototype to find better mechanical properties: surface conformity and thickness of the brace. It was found that the rubber brace used had the tendency to wrinkle, displacing the flex sensors further from the actual anatomy of the human arm at a given position. It may be possible to improve mounting without compromising the ability for actuation through a soft, pliable material.

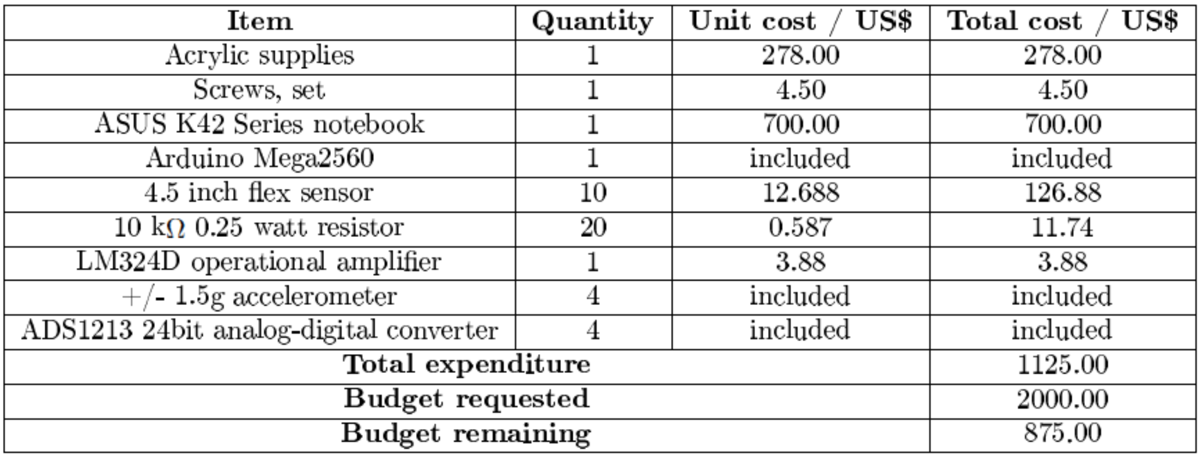
We identified no signs of degradation in the resistance readings of the sensors over 90 seconds test. Also, we are currently studying the durability of our flex sensors to ensure that the longevity of these sensors and their electro mechanical properties meet demands of a permanent assistive device.

As the data acquisition device was built for simple testing, we have yet to achieve the potential from our operational amplifier; the circuit topology is undergoing revision to eliminate noise from the op-amp;
and our sensor network can be optimized for faster sampling rate and sensitivity.

We plan to implement real motor actuation to the system to investigate the paradigm of closed loop control. We will follow an iterative step-by-step process and continuously optimize our system.

Appendix: Current budget summary

This section details the purchases that we had made using the AIP SPS funds, Table 1.



Item	Quantity	Unit cost / US$	Total cost / US$
Acrylic supplies	1	278.00	278.00
Screws, set	1	4.50	4.50
ASUS K42 Series notebook	1	700.00	700.00
Arduino Mega2560	1	included	included
4.5 inch flex sensor	10	12.688	126.88
10 kΩ 0.25 watt resistor	20	0.587	11.74
LM324D operational amplifier	1	3.88	3.88
+/- 1.5g accelerometer	4	included	included
ADS1213 24bit analog-digital converter	4	included	included
Total expenditure			1125.00
Budget requested			2000.00
Budget remaining			875.00

Table 1: Budget summary as of 15 June 2011.

References:

(1) Samuel B. Kesner, Leif Jentoft, Frank L. Hammond III, Robert D. Howe, and Marko Popovic, “Design Considerations for an Active Soft Orthotic System for Shoulder Rehabilitation,” accepted to the 33rd Annual International IEEE EMBS Conference, Boston, MA, August 30-September 3, 2011.

(2) A. R. Tilley A. R., H. Dreyfuss, The Measure of Man and Woman. Whitney Library of Design, Watson-Guptill Publications, New York, 1993.

(3) D. A. Winter, Biomechanics and Motor Control of Human Movement, Wiley, New York, 1990.