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Source of Work Area Reduction Following Hemiparetic Stroke and Preliminary Intervention Using the ACT ^{3D} System

Theresa M. Sukal, Michael D. Ellis, Julius P.A. Dewald

Northwestern University Depts of Biomedical Engineering and Physical Therapy and Human Movement Sciences
645 N Michigan Ave, Suite 1100
Chicago, IL 60611 USA

Abstract—**The effect of gravity increases the expression elbow/shoulder synergy patterns results in discoordination during movements following stroke. The Arm Coordination Training 3-D (ACT ^{3D}) robotic system is a novel way of recording movement patterns while a subject generates varying amounts of shoulder abduction torque. This system is used to provide preliminary data that show reduced elbow extension and shoulder flexion capabilities as shoulder abduction requirements increase resulting in reduced work area at high shoulder abduction levels. Single subject data is highlighted to illustrate the application of an intervention aimed at progressively training subjects to overcome the effects of abnormal joint torque coupling on reaching abilities.**

I. Introduction

A stereotypical movement impairment often seen following a stroke is abnormal muscle coactivations that result in spontaneous coupling of movement at adjacent joints. These were first reported by clinicians [1,2], and were seen across many patients, regardless of lesion location and amount of spontaneous recovery. We first quantitatively characterized abnormal muscle coactivation and associated joint torque coupling under static conditions using a load cell to record joint torque patterns associated with maximum efforts in single degrees of freedom, and found that volitional shoulder abduction produces abnormal spontaneous elbow flexion activity in hemiparetic stroke subjects, and shoulder adduction efforts couple with elbow extension [3,4]. We later concluded that abnormal joint torque coupling explained restrictions in reaching following a stroke that cannot be attributed to simple muscle weakness, and showed that abnormal torque coupling between shoulder and elbow torques was seen even in mildly impaired subjects [6].

A series of studies have been done to explore aspects of arm movement following stroke, and how they are affected by the presence of gravity. First, an air bearing device was used to fully support a subject's arm on a frictionless surface, removing the need to activate antigravity shoulder muscles while performing point to point reaching movements. Subjects were able to reach much further away from their body when supported by the device, as compared to actively supporting the weight of their own arm against gravity [5,6,7].

To further investigate the effects of gravity, and percentages of gravity, on the functional workspace available to subjects following a stroke, the ACT ^{3D} system was used to create environments where an array of shoulder abduction levels were required to lift their limb off of a haptically rendered rigid surface. There was a significant effect of active limb support on the area subjects were able to cover with their impaired limb [8].

Here, we further investigate the source of work area reduction and present single subject data for using the ACT ^{3D} as an intervention tool. The ACT ^{3D} is used to deliver a targeted training program aimed specifically at reducing gravity-induced discoordination. Ellis et. al [9] have demonstrated, under an isometric training protocol, that it is possible to significantly reduce synergistic coupling in the impaired limb of chronic stroke subjects. This targeted intervention was successful in training individuals to support the weight of their limb while concurrently generating net elbow extension torques. It is hypothesized that the ACT ^{3D} will reduce abnormal torque coupling and furthermore improve reaching abilities due to the dynamic nature of the training protocol.

II. Methods

A. The ACT ^{3D}

A modified HapticMASTER robot (FCS Control Systems, The Netherlands) has been integrated with a Biodex experimental chair (Biodex Medical Systems, Shirley, NY) to form the first generation Arm Coordination Training 3-D (ACT ^{3D}) device, patent pending. This setup is ideal for measurement purposes because it allows movement in three dimensions, records endpoint forces with six degrees of freedom, and uses admittance control to prevent the perception of additional inertia by the subject. It can provide a very specific measurement of impairment by imposing forces on the arm to either counteract or enhance the effects of gravity, while concurrently collecting movement and torque data from the limb.

Information from sensors measuring the configuration of the gimbal attached to the HapticMASTER endpoint is used to provide real-time continuous visual feedback by way of an avatar of the arm displayed on a computer screen in front of the subject. The avatar is scaled according to anthropometric measurements from each subject. These limb length and sensor values are also saved for subsequent analysis and used to calculate elbow and shoulder joint angles.

The hand and wrist are placed in a neutral position in the splint to reduce spastic activity in hand and wrist flexors. The HM is connected to the same support track as the Biodex chair to allow relative and controlled movement and rotation with respect to one another, as seen in Figure 1. For both tasks described in the protocol section, the subject's trunk is immobilized by a set of straps and positioned at 90° of shoulder abduction when their arm is resting on the haptically rendered table. Further, this is an ideal system to use for a novel training program where subjects are trained to progressively regain the ability to simultaneously abduct at their shoulder and extend their elbow.

B. Protocol

The virtual effect of gravity can be enhanced or reduced by providing forces along the vertical axis of the ACT ^{3D}. Direction and magnitude of these forces dictates the perception of gravity alteration, and auditory feedback is used when the endpoint of the robot comes in contact with the haptic table during tasks where the subject must abduct to lift off the table. The amount of abduction torque required changed across trials. Throughout this protocol, percentages of active support were randomized between 0% where the weight of the arm is entirely compensated for to 200% where the subject has to generate abduction torques twice the size of those required to lift the limb against a normal gravitational force. Conditions are separated by 25% increments for a total of 9 active support conditions. Additionally, there is 1 condition of passive support, in which the subject is provided a rigid surface upon which to make reaching movements.

Figure 1. Subject shown sitting in the ACT ^{3D}. He is sitting on the Biodex chair with his arm resting in the splint attached to the HapticMASTER. The computer monitor in front of him shows an avatar of his arm.

Impaired and unimpaired limbs of 6 hemiparetic stroke subjects were tested on either the same day or within one week of each other. Subjects were asked to slowly make the biggest envelope possible with randomly ordered levels of support provided by the ACT ^{3D}. That is, they were asked to trace out with the end of their hand the greatest extent of reaching and retrieval they were able to, one trial in a clockwise direction and another trial in counterclockwise. The speed of movement was kept slow to minimize the influence of stretch reflexes and provide a picture of the best possible movement range. If they were unable to lift their arm under a particular condition, work area was considered to be zero and the condition was skipped.

The subject involved in the training program participated in therapy 3 times a week over a period of 8 weeks. Specifically, the subject was trained to reach outward towards virtually displayed targets in 5 locations while lifting off of the haptic table at a threshold level of active limb support. As the training period progresses, gravity was re-introduced in a progressive fashion. The effect of gravity re-introduction training on motor performance is being currently studied by comparing this protocol with a similar protocol where active support of the limb against gravity is not required. In this comparison group, subjects reach toward the same targets but are supported by a haptically rendered horizontal surface associated with the height of the shoulder. By comparing group performance on the metrics described in the first portion of the protocol the effect of re-introducing gravity will be elucidated.

C. Analysis Software

Joint angles were back calculated from the endpoint measurements recorded by the ACT ^{3D} to a known shoulder location in space using inverse kinematics and subject specific limb lengths. This was done at each point on the work area envelopes and can be expressed as single joint ranges of motion, or in the form of angle-angle plots, where

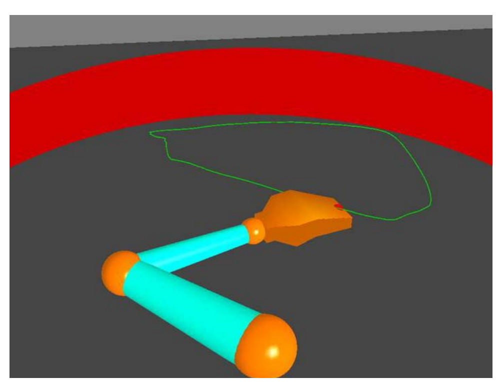


Figure 2. Example of the visual feedback a subject would receive when their left arm is being tested. The red arc represents full extension, based on arm length measures, and the green line traces the path of the finger tip during the task.

elbow angles are shown in relation to the simultaneous shoulder angle.

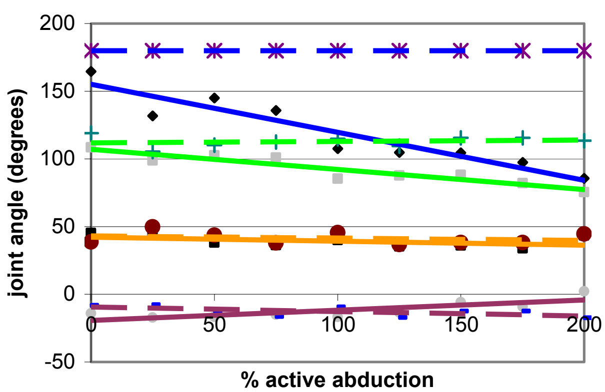
III. Preliminary Results

Previous results [7] showed a reduction in available work area with a qualitative observation that the greatest work area reduction is seen in the reaching portion of the movement, particularly in the direction of pure elbow extension. This is consistent with the flexion synergy hypothesis, that elbow flexion torque coupling grows steadily stronger as increased levels of shoulder abduction are required.

More explicit demonstration of the expression of synergy in stroke subjects can be seen when examining the available joint configurations at each level of active limb support requirement. The comparison of the impaired and unimpaired maximum excursion joint angle data from a representative subject is shown in Figure 3A. With linear regression of each of the joint angles, it can be seen that as abduction levels increase there is a trend for a decrease in both shoulder flexion and elbow extension, with elbow extension almost halved between 0% and 200% of active support. Although the steepness of the reduction in elbow extension and shoulder flexion as a result of active support varies across subjects, the trends of reduced capabilities in these degrees of freedom remain consistent. Figure 3B shows the grouped results for two support levels: 0% and 200%. There is a significant difference between these two levels in elbow extension and shoulder flexion, while shoulder extension and elbow flexion remain the same. These two changes explain the decrease in available work area at the different levels of abduction, and very specifically echo the behavior pattern of the flexion synergy. It can also be seen as a stark contrast to the unimpaired side, where there is no change or effect of abduction level (refer to the dashed lines in Figure 3A).

An example of a positive effect of the gravity reintroduction protocol is shown for a single subject in Figure 3. Over 8 weeks this subject was able to increase both the 100% and 200% active limb support work areas. Specifically, it can be seen with the aid of the gray limb segments that the area of greatest improvement resulted for an increased ability to simultaneously extend at the shoulder and elbow.

A.



B.

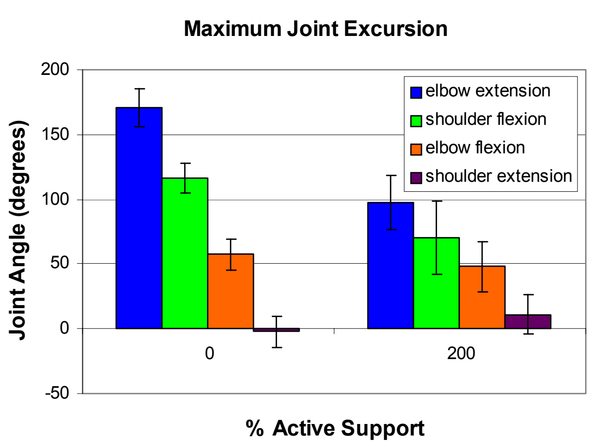


Figure 3: A. Joint angles as a function of active limb support. Blue corresponds to elbow extension; green to shoulder flexion; orange to elbow flexion and purple to shoulder extension. In each case, the dashed lines are the unimpaired side, while the solid lines represent the behavior of the impaired limb. Note the dramatic decrease in both elbow extension and shoulder flexion in the impaired side, as a result of greater abduction torques. B. Grouped average and standard deviations for 0% and 200% active limb support conditions.

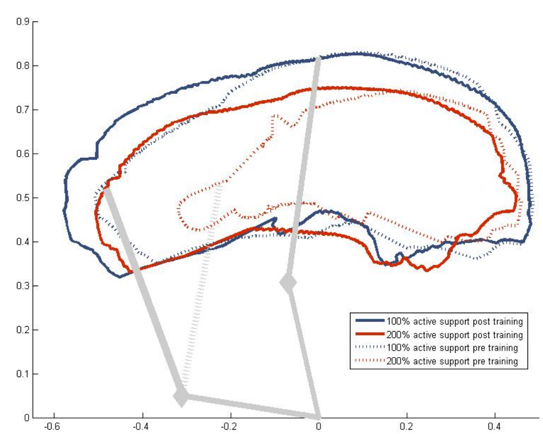


Figure 4: Results of training for a single left side impaired subject. Dashed red and blue lines represent work area achieved before training, and solid lines are following the training program. The gray segments represent the arm configurations in two shoulder joint angles. There is an overall increase in work area, and specifically an increase in elbow extension capabilities seen when the shoulder is more extended (compare the dashed and solid forearm-hand segments at the more extended position).

IV. Discussion

These preliminary results show that a hemiparetic stroke subject experiences a reduced work area as a result of actively supporting their limb weight against gravity. This can be explained by greater constraints of the flexion synergy as increasing amounts of shoulder abduction produce more spontaneous elbow flexion and reduced ability to reach out to places in the work area further from the body. Specifically, elbow extension capabilities are decreased, which has a direct and negative consequence on available work area. Being able to quantify the locations of compromised ability allows more targeted intervention programs to be designed, with potentially greater functional gains.

The ACT^{3D} can have a positive effect when used to train individuals with stroke to overcome the negative effect of synergies. Specifically, in one subject, we show that levels of abduction where work area was most compromised can be altered even years following the onset of stroke. Subjects are able to work within the ACT^{3D} environment to improve reaching patterns. A larger pool of subjects and comparison with the control protocol will provide a clearer picture of the importance of gravity reintroduction and movement on motor outcome improvement following stroke.

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