# Using the Kinect to Limit Abnormal Kinematics and Compensation Strategies During Therapy with End Effector Robots

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*Abstract*—**Abnormal kinematics and the use of compensation strategies during training limit functional improvement from therapy. The Kinect is a low cost ($100) sensor that does not require any markers to be placed on the user. Integration of this sensor into currently used therapy systems can provide feedback about the user's movement quality, and the use of compensatory strategies to complete tasks. This paper presents a novel technique of adding the Kinect to an end effector robot to limit compensation strategies and to train normal joint coordination during movements with an end effector robot. This methodology has wider implications for other robotic and passively actuated end effector rehabilitation devices.**

***Keywords—Stroke, therapy, robotics, synergies, haptics, coordination.***

## I. Introduction

Stroke can result in severe and long lasting disability [1]. The loss of independent joint movement and normal coordination is commonly observed in the affected arm after stroke [2] and is hypothesized to be the main impediment to functional use of the limb [3]. Abnormal muscle synergies impede normal coordination by causing unintended co-activation of muscles. For example, the flexor synergy results in simultaneous shoulder flexion and elbow flexion [4][5]. Individuals with disability due to chronic stroke frequently utilize compensation patterns, such as trunk movement and abnormal kinematics (internal rotation of the shoulder and shoulder hiking), to complete functional activities. These patterns are energy inefficient and may increase the incidence of disuse of the affected limb [6]. Research has shown that therapy interventions that encourage compensation strategies may limit functional recovery of the affected limb [7][8] Recovery of normal joint coordination is possible with a focused intervention [8] and may aid in real world use of the limb in activities of daily living [9].

The use of robotic devices to treat upper limb movement deficits is becoming increasingly prevalent, with various commercially available devices. A recent review of 19 studies showed positive outcomes in functional recovery but not in arm strength [10]. The wide variety of study designs, devices, and control methods make it difficult to compare systems.

Rehabilitation robots range from single joint training [11][12], to arm end effector robots [13][14], and full arm exoskeletons [15][16]. End-effector robots generally have lower cost, simpler controls, and lower impedance than exoskeleton robots but still allow multi-joint movement, which is more akin to functional use of the limb. The lower cost and ease of use of these robots makes them a more viable option than exoskeletons for home therapy use. Many end effector robots use end point tunnels to provide minimal guidance through the desired movement [17][18][19]. However, recent research by this author showed that individuals with chronic stroke will utilize compensation strategies when using end point tunnels. Individuals with stroke do not utilize these strategies with a joint-based progression limiting controller, Time Independent Functional Training (TIFT) [20]. In end point tunnels, users were able to use the walls of the tunnels to assist with the movement of difficult joints [20]. Furthermore, the study showed that subjects improve joint coordination during free movements after only ten movements with the TIFT mode.

The Kinect is a low cost ($100) vision based sensor that is commonly used for skeleton tracking in gaming environments. The Kinect does not require markers to be placed on the user, which allows for very quick and effortless setup. Joint angle measurements from the Kinect have been shown to be within a reasonable level of error for clinical use [21] and the rehabilitation potential of the Kinect is currently under investigation by several groups [22][23]. Although the Kinect has been used to provide therapy, it is unable to provide assistance or haptic feedback to users, which limits the potential user population to less affected individuals.

The following paper describes how the Kinect can be used to decrease compensation strategies and train normal movement kinematics during therapy with an end effector robot.

This paper acts as a proof of concept for future implementation with other rehabilitation robots and end point devices, which are used for therapy. This system would be especially beneficial for unsupervised therapy, such as in the home, where the clinician would not be available to continuously correct compensation strategies.

## II. The Combined Kinect and Robotic System

For this research the Force Dimension Delta 6 robot was used with the Xbox360 Kinect as shown in Figure 1. The Force Dimension Delta-6 robot is an end effector robot that is commonly used for surgical simulation. The device has a maximum applied force of 20N. The Delta-6 robot has active friction and gravity compensation. Although the robot has six degrees of freedom, only the three positional axes were used during this experiment due to concerns about the strength of the orientation joint motors. A custom wrist brace end effector was attached to the robot for more controlled hand orientation similar to what would be used in a therapy setting. The Delta-6 workspace is somewhat limited, but allows for basic reaching movements with a vertical (Y axis) range of 52 cm, and horizontal range (X axis) of 26 cm when the Z axis is fixed at the center of the robot. Due to the design of the robot, changes in the Z position will reduce the workspace of the robot. The Z axis was not used in the follow proof of concept.

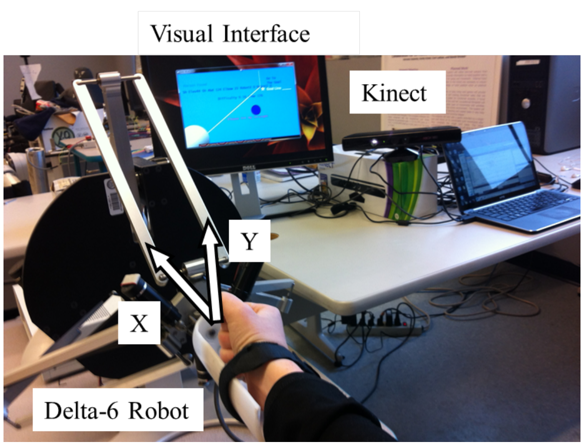



Fig. 1. The Kinect and Delta-6 system including the monitor with the visual interface

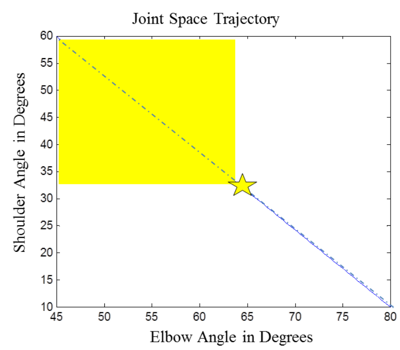
The Microsoft SDK v1.5 allowed for easy access to the skeleton tracking data. Joint angles were calculated with simple vector analysis. Recommended real-time smoothing parameters for gesture recognition were used on the skeleton tracking data to reduce signal noise. Smoothing was minimized to decrease potential effects of signal latency. The Kinect requires at least four feet of displacement from the user for accurate tracking. Although the user was seated during use of the robot, standing mode was utilized to ensure that the trunk angle is captured.

The Delta-6 was programmed in C, so a wrapper was used to integrate the robot into the C# platform. Visual Studio and Microsoft XNA were used for the visual interface. The visual display can provide feedback about the Kinect and robot measurements.

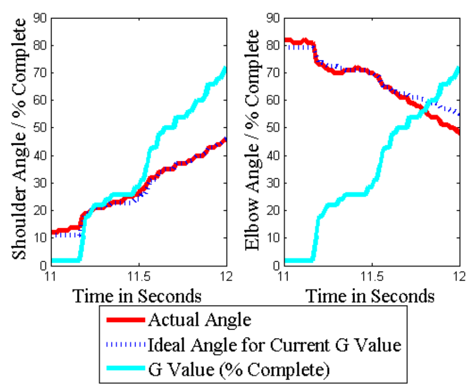
## III. Trajectory Progression

The goal of training is to encourage normally coordinated movement of multiple arm joints. Previous work with the Time Independent Functional Training (TIFT) modality has shown that the mode is effective at inducing normal joint coordination during training. Because of this fact, the TIFT modality was used with the combined Kinect and robotic system. The TIFT mode limits progression through a trajectory based on the lagging joint. The method is described in detail in Brokaw et al 2011[24]. The general principle of the methodology is the use of haptic walls to limit movement unless the user moves both control joints together. When using the Kinect, trunk angle can also be used to regulate task progression.

For example, if the task is to lift the shoulder and extend the elbow, the user would be required to coordinate these movements. Movement patterns within abnormal muscle synergies (Flexion Synergy: shoulder flexion and elbow flexion) would be prevented. Figure 2(a) shows an example of how this progression would work.




(a) Progression with TIFT




(b) Example of Change in G with Joint Position

Fig. 2. Example of progression with the TIFT method. The figure shows a path of shoulder elevation (increasing shoulder angle) and elbow extension (decreasing elbow angle). Progression occurs from the current position (yellow star) when the user enters the yellow space. Figure 2(b). shows this process in action. The G value (percent of trajectory completed) only increases when both joints are progressing in their trajectory. To progress, the shoulder angle must be above the ideal position at the same time the elbow angle is less than its the ideal angle.

From the current position on the trajectory the user needs to enter the yellow coordination space to continue progressing

[24]. This yellow goal space will move as the current trajectory position changes. 2(b) shows this process of changing the G value (percent trajectory completed) based on the coordinated progression of the shoulder and elbow. Only when the shoulder angle is larger than the current trajectory ideal angle and the elbow angle is less than the current trajectory ideal angle will G increase.

Three control cases were considered to evaluate the potential of using the combined Kinect and robot system. The cases were implemented, and data is presented from a single non-impaired user as a proof of concept. The first, and control case, implemented TIFT with robot position controlling the movement. The Kinect was only used to measure arm kinematics and did not impact the progression or haptic guidance of the movement through the task. The second case looked at the use of the Kinect measured arm angles for progression through the path but with haptic end point walls still enforcing movement along the robot end point trajectory. The third case looked at the implementation of Kinect measured arm angles for trajectory progression and simulated joint space haptic guidance.

An example trajectory based on reaching up to a shelf placed directly in front of the user was created (two dimensional movement). The desired trajectory was determined in arm joint and robot end point space based on kinematic patterns of the single non-impaired user. With normal posture, this path approximately aligns the hand/robot's movements on the X-axis with elbow extension, and the hand/robot's movement on the Y-axis with shoulder flexion. The Z-axis, corresponding to shoulder horizontal abduction, was fixed with haptic walls for the movement. The trajectories are shown in Figures 3, 5, and 7. Although other trajectories and other planes of movement could be used with this method, this trajectory was used as an example through-out this paper.

## IV. Case 1. End point based TIFT for Task Progression with End Point Haptic Guidance

The TIFT method of progression requires proper coordination of at least two joints to allow the user to move through the path. For certain trajectories, movement of joints can be inferred from end point movements. For our test case, movement in the X and Y axes was used to reflect elbow and shoulder movement, respectively. Movement through the path was controlled by robot end point position where the TIFT mode required coordinated movement in X and Y axes for progression. Haptic walls based on end point position error were used. This method eliminates the potential for users to drag or push along the walls, as they do in end point tunnels, to assist with completion of the movement. However, although the TIFT method eliminates some undesirable strategies seen with end point tunnels, it does not eliminate the use of abnormal kinematics. An example of this, implemented with our system, is shown in Figure 3.

Even though the robot endpoint position tracks the goal path, the non-impaired user was able to complete the task through the use of compensation strategies (torso lean) and did not obtain the desired range of motion or coordination pattern of the arm joints.

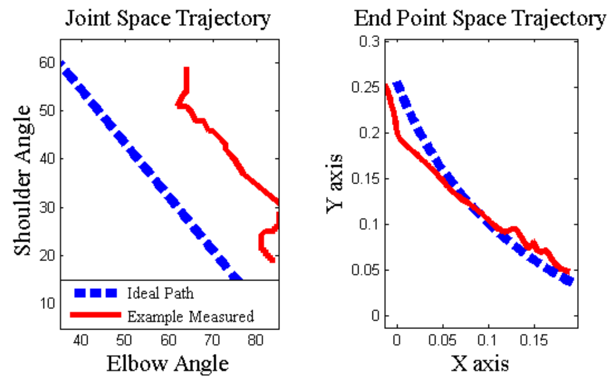



Fig. 3. The ideal trajectory is shown in dashed blue and one of the test trajectories for TIFT progression is shown in solid red. During this movement, path progression was controlled by the robot end point position (shown on right). As shown the user is able to use compensation strategies such as leaning to avoid normal movement range of motion and coordination.

## V. Case 2. Kinect Measured Arm Joint Coordination for Task Progression with End Point Haptic Guidance

After verifying that the use of the end point based TIFT progression method would not be enough to ensure normal joint coordination, the Kinect measured arm angles were used to control progression through the path. Depending on the system positioning, the Kinect may have trouble with continuous accurate movement tracking. Figure 4 shows an example movement pattern of the shoulder and elbow gathered from the Kinect with the individual seated and their arm in the end point robot (as shown in Figure 1). Figure 4 shows some noise in the collected movement data, and at 23.5 seconds there is an occlusion error resulting in a spike in the kinematic data. Some additional precautions were taken to ensure stability of the system. The system initially drives the hand to the start position and will not leave that mode until the Kinect has determined the position of the user for 10 seconds. This minimizes the risk of skeletal tracking errors.

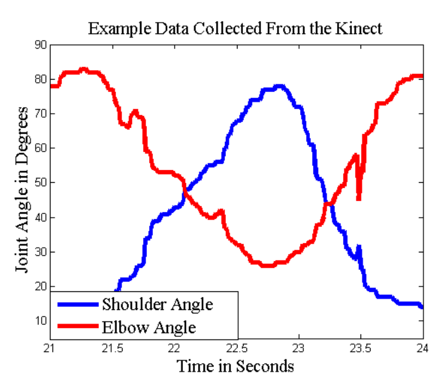



Fig. 4. Shoulder and elbow angles measured from the Kinect during one complete movement starting with the shoulder down and elbow flexed,punching out forward and up, then back to start. This figure shows some signal noise and a moment of occlusion occurs at 23.5 seconds.

Even with these errors the Kinect-measured arm and trunk angles can easily be used to limit progression through the trajectory and to provide feedback about joint position. In this case the progression can be determined by the user's joint space movements, while the haptic forces are determined by robot end point error. This still eliminates the potential use of compensation strategies for task completion and results in more coordinated movement of the shoulder and elbow during training as shown in Figure 5. Note that the robot's end point path is still well preserved within end point error based haptic walls. During these movements feedback about joint space

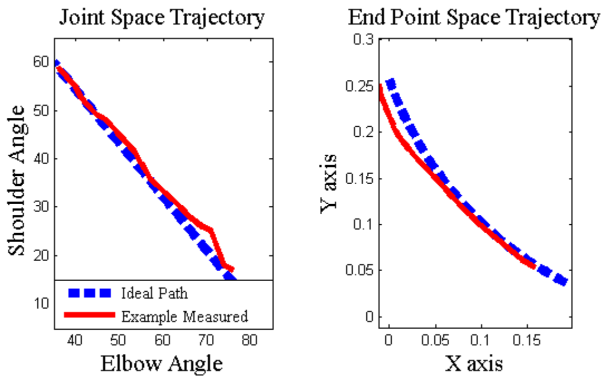



Fig. 5. The ideal trajectory is shown in dashed blue and one of the test movements using joint space progression is shown in solid red. Coordinated movement of the shoulder and elbow are used to progress the individual through the robot's end point path with haptic end point walls.

position relative to the goal must be provided to aid with task progression. An example visual interface, shown in Figure 6, provides joint position feedback to help guide the user's movement. The ball is moved by the user's joint positions; shoulder controls vertical and elbow controls horizontal, since these joints control progression through the path. Additionally the system displays an error message to help correct the user's posture.

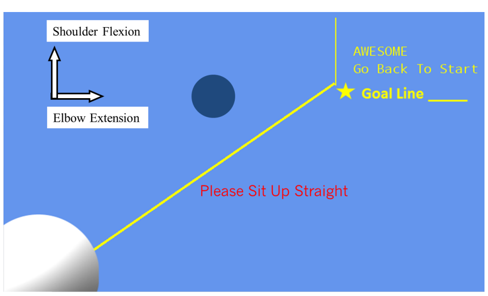
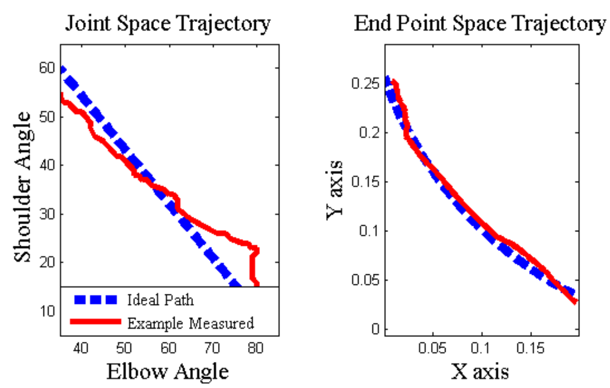


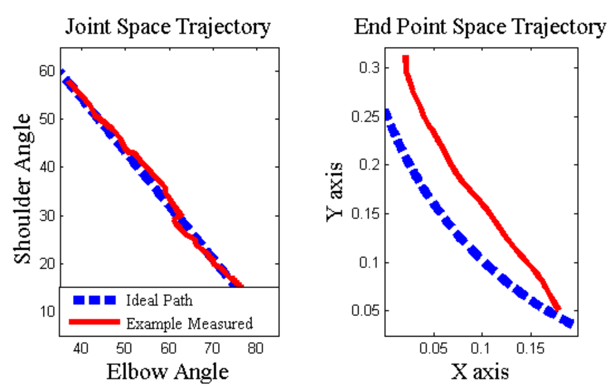

Fig. 6. Example visual interface for the system. The dark blue ball is moved horizontally by elbow flexion/extension and moved up and down via shoulder flexion. The system also provides feedback about the user's posture, which can also be used to limit trajectory progression.

## VI. Case 3. Kinect Measured Arm Joint Coordination for Task Progression with Joint Space Haptic Guidance

The ideal method of haptic guidance would give feedback based on the arm joint position error, which is controlling trajectory progression. This would provide the most intuitive information about when the user is not performing the correct joint coordination. This may not be possible for some situations where the Kinect can not reliably establish the location of the user's arm in the robot. The real-time smoothing parameter of the Kinect skeleton data may need to be increased. However, the resulting latency could also lead to instability. A safety was implemented where the signal would be ignored if the measured angle was more than 20 degrees away from the current ideal angle position in the trajectory. This removes the potential for sudden force due to an occlusion error. In order for the feedback to be intuitive in joint space, the inverse of the human arm's Jacobian transposed was used to calculate the end point forces to be applied by the robot to simulate the joint space torques calculated from the joint space errors. Figure 7 shows the movement with implementation of the haptic walls in joint space. Figure 7(a) shows an example of a typical movement where both joint angle and end point space paths are well aligned with the ideal paths. In Figure 7(b) the non-impaired user intentionally leaned forward resulting in a change in the robot's end point position off of the previously used ideal robot end point trajectory. This shows that, regardless of robot end point position, the system still ensures that the user maintains joint coordination along the desired joint space trajectory.




(a) Normal Movement with TIFT Progression and Joint Space Haptic Guidance




(b) Deviation from Original Robot End Point Path

Fig. 7. Trajectory progression with haptic joint space feedback. (A) The top figure shows movement through the path without compensation strategies. (B) During this movement the non-impaired user intentionally leaned forward. The system guided the user to normal joint coordination and allowed error of the end point robot from its ideal path.

It should also be noted that in this mode leaning forward and bending the elbow will result in the robot pulling the user's arm forward to maintain the elbow angle. However, this will not lead to progression and thus cannot be used as a compensation strategy because progression is dependent on extending the elbow beyond the current angle on the trajectory. Although this system was implemented with a reaching task, horizontal planar robots are probably the best use case for this method to minimize the effects of occlusion and avoid issues of instability.

## VII. Conclusion

The prevention of abnormal movement strategies has the potential to improve robotic therapy outcomes. This pilot research with an non-impaired user showed that a purely end point based version of the TIFT modality alone (case 1) is not sufficient to prevent compensation strategies, but joint coordination can be trained with an end point robot through the use of the Kinect. Case 2, robot end point error haptics, and case 3, arm joint error haptics, both induced normal joint kinematics. Case 2 will be the easiest method to implement with most robotic systems and is sufficient to eliminate compensation strategies. However, it provides less intuitive haptic feedback than case 3 about the desired movement path.

For simplicity, a two dimensional path was used for this proof of concept and the robot's third positional axis was fixed with haptic walls. A three dimensional path, with horizontal shoulder abduction, could certainly have been implemented with this robot and Kinect system. However, increasing the number of control arm joints beyond the number of end point position axes would result in redundancy that would be difficult to resolve for haptic feedback. Many arm joints could certainly be used to control movement progression, as in case 2. However, in both cases detailed visual feedback would be required to inform the user what joint was causing them to encounter a haptic wall. Visual feedback about abnormal movement of the trunk and shoulder internal rotation, in coordination with the two dimensional Kinect controlled solution, may suffice to reduce the impact of these common compensation patterns.

The Kinect is a low cost system that can be integrated into current rehabilitation devices. The low relative cost of end point devices combined with the Kinect could make this a viable system for home use. In the clinic the Kinect's low setup time and cost would also make it preferable to complex, though more accurate, motion tracking systems. The combined system of the Kinect and end point robot could allow for joint coordination training that was previously limited to exoskeleton robots. Even if individuals do not wish to utilize the Kinect to turn their end effector devices to joint space control, the integration of the Kinect could provide these researchers with additional data about the movement of the arm joints and if the subject is using compensatory strategies.

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