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Manipulating Abnormal Synergistic Coupling of Joint Torques Through Force Applications at the Hand: A Simulation-Based Study

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Abstract

Loss of independent joint control due to abnormal coupling of shoulder and elbow torques (i.e., abnormal synergies) is a common impairment after stroke and has been linked to poor upper-extremity function in stroke survivors. Previous research has shown that the flexor synergy (i.e., shoulder abduction coupled with elbow flexion) can be treated by progressively increasing shoulder abduction loading during elbow extension exercises. However, this finding has not been implemented in planar reaching exercises, as this requires a clear understanding of the relationship between external forces on the hand and elicited joint torques when reaching for different targets on a table. The objective of this study was to model this relationship and determine reach/force combinations that could be used to counteract either the flexor or extensor synergies. We used a musculoskeletal model to compute shoulder and elbow joint torques when reaching for targets on a table against different force directions and magnitudes. We found that force direction modulated the coupling of shoulder and elbow torques and force magnitude scaled each torque uniformly such that the extent of coupling remained the same. Additionally, we found that forces on the hand could be used to gradually increase the magnitude of simultaneous shoulder and elbow torques that counteract either the flexor or extensor synergy. These results provide the foundation to develop therapeutic interventions that address abnormal joint couplings following stroke using forces on the hand during planar reaching. Future studies should examine the therapeutic benefits of these findings in patient populations such as stroke.

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Conflict of Interest Statement
The authors declare no conflicts of interest

Keywords

Rehabilitation robotics; motor control; motor coordination; low cost; OpenSim

Introduction

Stroke affects millions of people every year and many who survive suffer from motor impairments (WHO, 2002). One such motor impairment is abnormal muscle coordination, which can often hinder independent joint control. For example, the "flexor synergy" in stroke survivors refers to shoulder abduction coupled with involuntary elbow flexion, forearm supination, and wrist and finger flexion (Dewald et al., 1995; Twitchell, 1951). This abnormal flexor synergy results in a significant loss of independent joint control and has been shown to contribute to upper-extremity functional deficits more significantly than muscle weakness (Beer et al., 2007; Sukal et al., 2007) or spasticity (Ellis et al., 2017). Stroke survivors often compensate for the lost independent joint control by leaning forward to reach for objects rather than extending their elbow. This can help a stroke survivor accomplish daily tasks (e.g. reaching for a glass, brushing teeth, etc.) but long-term reliance can prevent the restoration of healthy movements (Levin et al., 2009). Therefore, experts have recommended that post-stroke rehabilitation should directly address the flexor synergy and its complement: the extensor synergy (i.e., coupled shoulder adduction with elbow extension, forearm pronation, and wrist and finger flexion (McPherson and Dewald, 2019)) (Ellis et al., 2016, 2017)

Previous research on flexor and extensor synergies has revealed meaningful information and methods to target them in rehabilitation. Specifically, prior studies have shown that volitional elbow extension reduces as shoulder abduction torque increases (Dewald et al., 1995; Sukal et al., 2007), and likewise elbow flexion reduces as shoulder adduction torque increases (McPherson and Dewald, 2019). This discovery prompted studies during which participants progressively increased their shoulder abduction torque during elbow extension exercises. After several weeks of training, participants improved in both kinematic and clinical measures of impairment (Ellis et al., 2009, 2018). While no similar study has been conducted for the extensor synergy, both synergies are believed to result from increased reliance on contralesional cortico-bulbospinal motor pathways and can co-exist in stroke survivors (McPherson and Dewald, 2019). Therefore, one could reasonably expect that progressively increasing shoulder adduction during elbow flexion movements would also benefit patients with this motor impairment. While the paradigm of combining shoulder abduction with elbow extension exercises has significant clinical potential, previous studies have performed this training isometrically at 90° of shoulder abduction (Ellis et al., 2009, 2018), which has some limitations. First, isometric shoulder abductor contractions may not translate to dynamic tasks, which are commonly involved in many activities of daily living. Further, reaching with 90° of shoulder abduction may not be functionally relevant to typical usage of the upper-extremities (e.g., reaching for an object on a table), which is critical to induce experience-dependent plasticity (French et al., 2009; Kleim and Jones, 2008). Additionally, targeting both synergies (i.e., flexor and extensor) in a continuous training session would require a device that quickly transitions between shoulder abduction and adduction torques. This is possible with an active (motorized) device, but such a device would be expensive, clinically impractical, and potentially harmful to the user if the device malfunctions (Chang et al., 2018). Therefore, to expand the clinical potential of these training paradigms, we should reformulate them so that they are relevant to functional tasks and safe and inexpensive to implement.

One approach to address abnormal torque coupling (caused by abnormal synergies) is by applying controlled forces to a participant's end-effector (i.e., hand) as they reach for objects on a table (Figure 1A). For instance, a right-handed reach forward along a straight-line path requires the participant to extend their elbow (Figure 1B). A force pointed towards the participant's midline perturbs their hand motion, requiring them to generate a shoulder abduction torque to counteract the perturbation and maintain the desired trajectory. Therefore, it may be possible to target abnormal joint couplings during reaches for targets on a table using the progressive loading approach discussed above (Ellis et al., 2018). Reaching for objects on a table is more typical for the upper-extremity. Also, training like this would be inexpensive and safe because it can be easily paired with existing clinical therapies (e.g., table slides) and rehabilitation robots (Chang et al., 2018; Hogan et al., 1992; Kikuchi et al., 2009; Saracino et al., 2016; Washabaugh et al., 2019). Further, we can conceptualize this training during table-level reaching as a type of "functional resistance" or "functional strength" training for the flexor/extensor synergies. Functional resistance training is an approach where the muscles are loaded in a task-specific manner to combine therapeutic gains from both task-specific training and strength training (Washabaugh et al., 2020). This combination allows for uniquely beneficial rehabilitation approaches (Brown et al., 2021; Donaldson et al., 2009; Graef et al., 2015). However, before a designing a therapeutic intervention using this approach, we must first determine methods of using forces applied to the hand to progressively increase simultaneous joint torques at the shoulder and elbow that counteract post-stroke synergies during planar reaching.

Therefore, the objective of the current study was to evaluate how forces applied on the hand could manipulate joint torques during planar reaching and identify methods of progressively increasingly simultaneous joint torques that target abnormal joint couplings typically found in stroke survivors. Simulation-based analysis in OpenSim of a musculoskeletal model was used to find joint torques while a participant reached for different targets. For each target, we found the joint torques required to reach the target against different forces on the hand. We then computed two outcome metrics to quantify how forces applied on the hand manipulated individual joint torques (torque ratio) and the extent of synergistic shoulder and elbow torque coupling (coupling factor). We found that, during a given reach, changing the force direction modulated shoulder abduction/adduction (ABD/ADD) and elbow flexion/extension (FLEX/EXT) torques. Further, we found that force directions could be selected to increase simultaneous shoulder abduction/elbow extension and shoulder adduction/elbow flexion torques, which could be used to target abnormal synergies after stroke.

Methods and Materials

We used a simulation-based analysis of an upper-extremity musculoskeletal model to obtain joint torques during reaches for targets on a horizontal table (i.e., planar reaching). In our analysis, we considered many different force-field conditions. Broadly, our analysis can be summarized as follows:

1. Kinematic data were collected from a healthy participant while they performed planar reaches in a multitude of directions. During these reaches, no external force was applied to the participant's hand. The kinematic data were used to provide the musculoskeletal modelling software with reasonable joint trajectories to use as a template for all of our simulation-based analyses.

2. The musculoskeletal modelling software used the collected kinematic data to simulate the joint torques that would be required to generate the recorded movements. Of the joint torques, we analyzed shoulder abduction/adduction (ABD/ADD) and elbow flexion/extension (FLEX/EXT) because they are critical components of typical synergies in stroke survivors.

3. We repeated the simulation of the joint torques multiple times. In each repetition of the simulation, a simulated external force was applied to the hand of the model. In between repetitions, we changed magnitude and/or the direction of this simulated force and observed the change in simulated joint torques. Therefore, *each repetition applied a simulated force to the model's hand and solved for the joint torques that a healthy participant would need to exert to generate the empirical kinematic data.*

A simulation-based analysis was used (instead of collecting data from humans) because our aim was to generate a detailed model of the relationship between the forces on the hand and joint torques across a multitude of reach directions, which would not be feasible in human subjects experiment. Further, simulation-based analysis allowed us to enforce identical kinematics in different force conditions and remove the confounding effects of fatigue and motor adaptation during force-field experiments. The specifics of each part of our experimental protocol are discussed below.

Collection of template kinematic data

We created a kinematic model of a healthy participant performing planar reaches to serve as a template for all of our simulation-based analyses. The details of this model can be found elsewhere (Augenstein et al., 2020; Delp et al., 2007; Saul et al., 2015). Briefly, the kinematic model was created by recording the three-dimensional kinematics of a participant when performing a total of 36 reaches (Figure 2A). Each reach started from a "home" position: the location of the participant's right hand with their elbow flexed to 90° and their shoulder and wrist in neutral positions. From the home position, the participant traced straight lines (i.e., reaching trajectories) to targets 15 centimeters away. Each trajectory was defined by a unique θ, defined as the angle relative to the trajectory of a reach to the participant's right (shown as 0° in Figure 2A). θ was 0° on the initial reach, and each reach that followed was rotated counterclockwise by 10° such that $\theta = 350°$ on the final reach. Each reach was limited to the "home-to-target" portion of the motion - i.e., we did not consider the interval as the hand returned from the target to the home position. For discussion purposes, we referred to $\theta \in [0,90)$ as "Quadrant 1" or Q1, $\theta \in [90,180)$ as Q2, $\theta \in [180,270)$ as Q3, and $\theta \in [270,0)$ as Q4. The participant was instructed to perform each reach at their preferred speed (2.81s +/− 0.30s)(mean +/− st. dev.). Visual feedback of the home position, the current target, the trajectory, and the position of the participant's hand were presented on a monitor in front of the participant using a previously-developed planar reaching rehabilitation robot (Chang et al., 2018). It is important to note that this kinematic data set is used in all subsequent simulation-based analyses.

Simulation-based analysis

The simulation-based analysis used to compute joint torques is shown in Figure 2B. The musculoskeletal model had 7 DOF and was capable of modeling dynamic behavior of the right upper-extremity (Delp et al., 2007; Saul et al., 2015). Joint torques about each model DOF were simulated by inputting the empirical kinematics and a data file describing the simulated external forces applied to the participant's hand into OpenSim's Inverse Dynamics Tool. The effects of gravity were ignored during the simulation. The joint torques during each reach were interpolated to 100 evenly-spaced samples. The shoulder joint torques outputted by the Inverse Dynamics Tool were then transformed into coordinates relative to the model's torso to get shoulder ABD/ADD torque.

This inverse dynamics process (i.e., simulating all reaches) was repeated for each unique end-effector (i.e., hand) force. We defined a unique hand force as a unique pair of magnitude (in Newtons) $|F|$ and direction ϕ (in degrees). ϕ is the angle between the hand force and the reaching trajectory (Figure 2C). Therefore, we describe the force direction in terms relative to reaching trajectory, not in absolute coordinates (i.e., forces with the same ϕ on different reaches will have different directions on the table). ϕ is either a counterclockwise (CCW) or clockwise (CW) rotation from the reaching trajectory. We investigated $|F|$ = 10, 20, 30, 40, 50, and 60N and all ϕ between 45° CCW and 45° CW in 2.5° increments, totaling to 7992 Inverse Dynamics executions (6 magnitudes × 37 force directions × 36 reaching directions). These force directions and magnitudes were selected to reflect what would be possible in a future therapeutic intervention with either an existing rehabilitation robot or conventional equipment used in clinics. Torque was normalized to the peak torque observed during all force and reach conditions.

Outcome Metrics

Our analysis was limited to shoulder ABD/ADD and elbow FLEX/EXT torques, and our two primary outcome metrics were "torque ratios" and "coupling factors". The torque ratio expressed how the *direction* of the forces applied on the hand altered torque contribution. Specifically, the torque ratio for a given reach, force magnitude, and force direction was computed by dividing the average torque by the average torque recorded during the same reach and force magnitude with force direction $\phi = 0°$. For example, the shoulder ABD/ADD torque ratio during a reach with a $|F|, \phi$ = 40N, 45° force was found by dividing the average torque during this force condition by the average torque during the same reach with a $|F|, \phi$ = 40N, 0° force. Torque ratios with magnitude > 1 denote instances where the force direction increased the torque contribution above the $\phi = 0°$. Torque ratios that are < 0 denote a change in torque direction relative to the non-steering case.

The objective of the coupling factors was to expose reaches that could be potentially useful in a future therapeutic intervention. Specifically, this means finding reaching directions that could be used to counteract a post-stroke synergy by progressively increasing simultaneous joint torques in the shoulder and elbow through choices of different forces on the hand. For example, to counteract the flexor synergy, the intervention would start with a reach and force direction that minimized simultaneous shoulder abduction and elbow extension torque, and then progressed gradually to increase these torques by changing the force directions (Ellis et al., 2009, 2018). We computed two coupling factors: simultaneous shoulder abduction and elbow extension torque (ABD/EXT) and simultaneous shoulder adduction and elbow flexion torque (ADD/EXT). A reach that achieved a high ABD/EXT coupling factor would be a potential candidate for an intervention that addresses the flexor synergy. Similarly, a reach that achieved a high ADD/FLEX coupling factor would be a potential candidate for an intervention that addresses the extensor synergy. Quantitatively, the coupling factors were found using Equation (1).

$$\begin{gathered}\text{Coupling Factor}_{\text{ABD/EXT}} = 0.5 \times [(\tau_{\text{ABD}} - \hat{\tau}_{\text{ABD}}) + (\tau_{\text{EXT}} - \hat{\tau}_{\text{EXT}})] \\ \text{Coupling Factor}_{\text{ADD/FLEX}} = 0.5 \times [(\tau_{\text{ADD}} - \hat{\tau}_{\text{ADD}}) + (\tau_{\text{FLEX}} - \hat{\tau}_{\text{FLEX}})]\end{gathered} \tag{1}$$

In Equation (1), τ denotes the joint torque measured during a reach with some force magnitude and direction. $\hat{\tau}$ denotes the joint torque measured during the same reach with the same force magnitude, but the force direction ϕ selected to minimize the relevant shoulder torque (shoulder abduction torque for the ABD/EXT coupling factor, and shoulder adduction torque for the ADD/FLEX coupling factor). We used the difference between the torques measured during these two force conditions to penalize reaches with high shoulder abduction or adduction torque regardless of the choice of force direction and magnitude. Further, we used the average of the shoulder torque difference and the elbow torque difference to reward instances where both the relevant shoulder and elbow torques were simultaneously high. The ABD/EXT coupling factor was greater than 0 only when the shoulder was abducting (i.e., instances when the shoulder was adducting automatically received a value of 0). Likewise, while computing ADD/FLEX coupling factor, instances when the shoulder was abducting were set to zero.

Results

The reach-averaged shoulder ABD/ADD torque and elbow FLEX/EXT torque during different force conditions for several representative reaching directions are provided in Figure 3. The peak shoulder ABD/ADD and elbow FLEX/EXT torques across all reaches and forces were 17.4 Nm and 11.2 Nm, respectively. Both shoulder and elbow joint torques were modulated by the force direction, and this modulation scaled with the force magnitude. The ability to modulate shoulder ABD/ADD and elbow FLEX/EXT torques was also related to the reach direction (Figure 4). Namely, reaches in Q2 and Q3 offered greater ability to modulate shoulder adduction and elbow flexion, while shoulder abduction and elbow extension could be modulated during reaches in Q1 and Q4.

The torque ratios varied with both reaching direction and force direction (Figure 5). Specifically, reaches closer to 90° and 270° created the greatest variation in torque ratios with force direction for both shoulder ABD/ADD and elbow FLEX/EXT (Figure 5). Additionally, the torque ratios for each force magnitude were nearly identical (Figure 5), showing again that magnitude only scaled joint torques instead of altering one joint torque relative to another joint.

The ABD/EXT and ADD/FLEX coupling factors varied with both reaching direction and force direction (Figure 6). Reaches in Q1 and Q4 offered the greatest control over the ABD/EXT coupling factor while reaches in Q2 and Q3 offered greater control over the ADD/FLEX coupling factor (Figure 7). The reaches that achieved the highest ABD/EXT coupling factor were $\theta = 50°$ and 300°, while the reach that achieved the highest ADD/FLEX coupling factor was $\theta = 150°$. For each reach, a force direction maximized the relevant coupling ratio, many times this maximum occurring between the 45° CCW and 45° CW.

Discussion

The purpose of this study was to investigate how external forces applied to the hand during planar reaching could be used to progressively increase simultaneous joint torques that counteract typical post-stroke synergies. We found that the direction of the end-effector (i.e., hand) force modulated the recruitment of shoulder and elbow joint torques. More specifically, force directions could be selected to (1) increase coupled shoulder abduction and elbow extension torques in the right-hand side of the workspace (Q1 and Q4) and (2) increase coupled shoulder adduction and elbow flexion torque in the left-hand side of the workspace (Q2 and Q3). We also found that force magnitude did little to modulate the relative recruitment of joint torques, but instead scaled all joint torques. These findings indicate that forces on the hand can be manipulated to modulate torque coupling of the shoulder and elbow joints. The findings also have important clinical implications, as prior research indicates abnormal torque coupling contributes to loss of arm function after stroke and that rehabilitation interventions targeting abnormal joint coupling can help restore arm function after stroke (Ellis et al., 2009, 2018; McPherson and Dewald, 2019).

The coupling factors reveal several pieces of interesting information regarding the usefulness of certain reaches in counteracting the flexor and extensor synergies. $\theta = 50°$ and 300° had the highest ABD/EXT coupling factors, suggesting that these reaches are the best candidates for an intervention targeting the flexor synergy. This result arises from the range of possible shoulder abduction torques along these reaches. For example, shoulder abduction and elbow extension torque neared their global maxima along the $\theta = 50°$ with a force direction of $\phi = 45°$ CW, but also approached zero along the same reach with a force direction of $\phi = 45°$ CCW. Therefore, by simply sweeping the force direction gradually from $\phi = 45°$ CCW to 45° CW, it was possible to progress shoulder abduction and elbow extension torques from nearly zero to maximum along the same reach. Conversely, the ABD/EXT coupling factor was quite low during $\theta = 0°$, suggesting that this reach would *not* be an ideal candidate to counteract the flexor synergy. This is a useful realization because shoulder abduction torque and elbow extension torque are quite high in this reach direction, which would suggest the opposite conclusion. Following the previous research discussed above (Ellis et al., 2009, 2018), a reach is only useful to a future therapeutic intervention if the relevant shoulder torque can be increased progressively, as it allows the training difficulty to be increased gradually. $\theta = 0°$ received a low coupling factor because it elicited high abduction torque on all force directions included in our analysis. Further, reaches near the $\theta = 90°$ direction did not maximize either coupling factor, but instead offered the ability to target either the flexor or extensor synergy with moderate success, depending on the force direction. This was shown by both the ABD/EXT and ADD/FLEX coupling factors achieving moderately high values during reaches in these directions (Figure 7). This is an interesting result because the flexor and extensor synergy are characterized by opposite joint torques, yet our results suggest that they can both be targeted in the same reach by simply changing the hand force direction.

Although no other study has performed a similar examination of the relationship between forces on the hand and joint torques, our results are partially validated by a previous study that examined changes in shoulder and elbow muscle activation based on different hand steering forces when reaching at $\theta = 90°$ (Chang et al., 2018). The authors found that a 45° CW force simultaneously increased medial deltoid and triceps brachii activation, while a 45° CCW force simultaneously increased pectoralis major and biceps brachii activation. Our results show the same result, i.e., shoulder abductors and elbow extensors are more engaged with a 45° CW force and shoulder adductors and elbow flexors are more engaged with a 45° CCW force (Figure 3). Therefore, their results validate, at least partially, that forces on the hand that resist a participant's motion can elicit joint torques that counteract post-stroke synergies. However, the authors of this study only considered a reach along the $\theta = 90°$ trajectory. Therefore, future studies must be conducted to validate our findings in more reaching directions.

One strength of targeting abnormal joint coupling during planar reaching is that it can be easily integrated into many existing rehabilitation platforms. For example, many existing rehabilitation robots were designed to apply targeted resistance during this type of reaching (Chang et al., 2018; Hogan et al., 1992; Saracino et al., 2016). More generally, this paradigm could be implemented during many standard clinical exercises. For example, upper-extremity towel slide exercises are quite common in stroke rehabilitation. During these exercises, the patient places their hand on top of a towel resting on a table and then proceeds to extend their arm forward, using the towel to decrease friction. This exercise could be easily modified to target the flexor synergy by having a clinician perturb the patient's reaching arm toward their midline as they reach forward (Figure 8). Such an augmentation to an existing therapy exercise would be inexpensive, as it requires no additional equipment and minimal training to implement. Further, a clinician could easily train a person who spends time with the patient outside of the clinic (e.g. spouse, son/daughter, caregiver) to administer the training. This would dramatically increase the participant's training dosage by allowing them to train from home, which is a key determinant of rehabilitation outcomes (Lang et al., 2015).

It is important to note that we analyzed joint torques collected during a simulation of a musculoskeletal model performing stereotypical reaches in the horizontal plane. We chose this approach over recording torques from healthy participants because our objective was to create a detailed model of how forces on the hand influenced joint torques. We note that the kinematic trajectories recorded without any external forces were assumed to be similar to those with external forces. We believe that this assumption is reasonable, as healthy participants can typically perform consistent reaches with visual feedback when the movements are not very fast, and the external forces are not very high. Moreover, our results are consistent with prior experimental findings (Chang et al., 2018). Hence, we believe that our results are relevant to healthy participants; however, it is currently unclear how our results will transfer to a stroke population. The movements of stroke survivors are influenced by weakness, spasticity, and abnormal joint couplings, and would likely often differ from the kinematics analyzed in this study, especially when resisted by forces on the hand. However, these effects could be mitigated in a future therapeutic intervention by progressively increasing the end-effector (i.e., hand) force magnitude and enforcing the correct kinematics via visual feedback. Therefore, we do not believe that this shortcoming will influence our main findings or their transfer to a future therapeutic intervention. However, more research on stroke survivors is needed to verify this premise and to fully understand how different forces applied on their hand affect the shoulder/elbow torque coupling.

In summary, the results of this study establish a detailed model of how forces on the hand influence joint torques during planar reaching, and how these forces can be used to progressively increase joint torques that counteract post-stroke synergies. The results indicate that forces applied to a participant's hand while performing planar reaching can alter coupling of shoulder and elbow joint torques in a predictable manner. The established relationship between forces on the hand and joint torques could serve as a basis on which clinicians could target abnormal joint coupling when treating stroke survivors. Future work should utilize the findings in this study and apply them to a clinical population to test if this approach to targeting abnormal joint coupling does offer therapeutic benefits.

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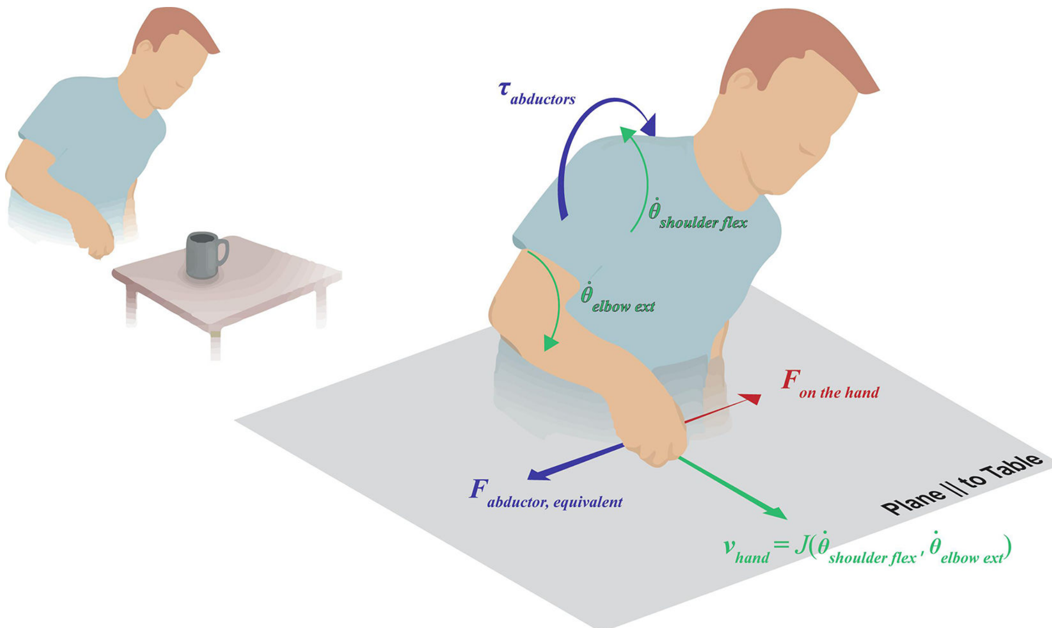

Figure 1:

Visual demonstration of how end-effector (i.e., hand) forces can elicit shoulder torques. Hand velocity along a forward reach ($\boldsymbol{v_{hand}}$) is mostly a function of Jacobian matrix J, shoulder flexion velocity $\left(\dot{\theta}_{shoulder\ flexion}\right)$, and elbow extension velocity $\left(\dot{\theta}_{elbow\ extension}\right)$. An external force applied to the hand that perturbs the motion ($\boldsymbol{F_{on\ the\ hand}}$) must be counteracted by the participant to maintain $\boldsymbol{v_{hand}}$. Increasing shoulder flexion/extension or elbow flexion/extension torques is not appropriate because $\boldsymbol{F_{on\ the\ hand}}$ is close to parallel with both torque axes. However, the shoulder abductors ($\boldsymbol{\tau_{abductors}}$) are capable of generating a torque that equates to a force $\boldsymbol{F_{abductors,\ equivalent}}$, equal to and opposite of the $\boldsymbol{F_{on\ the\ hand}}$.

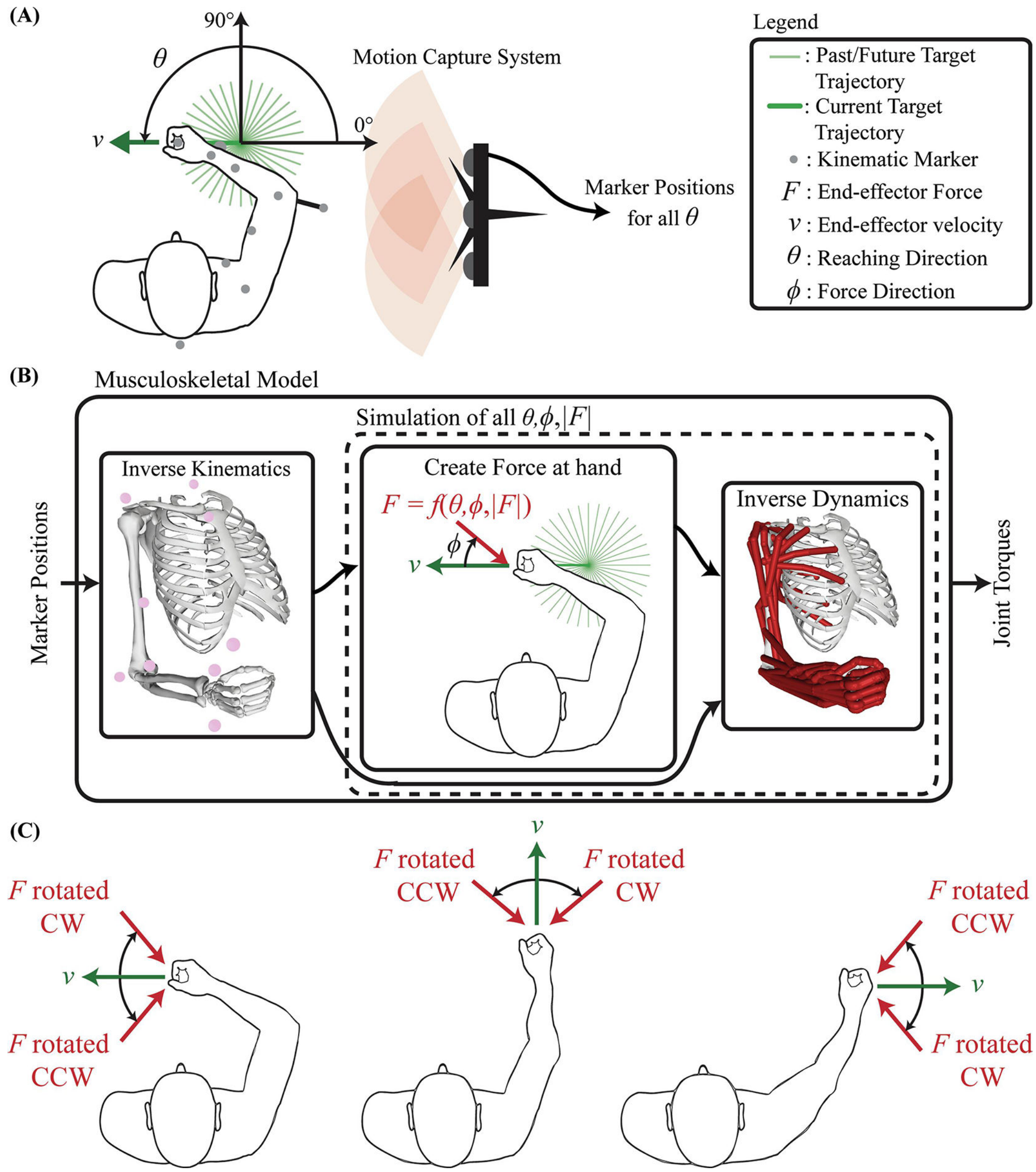

Figure 2:

A visual depiction of the experimental procedure. (A) Data collection phase: The kinematics of a participant were recorded while they reached for 36 different targets on a horizontal table. (B) Simulation phase: For each reach, we simulated the joint torques exerted during different force directions and magnitudes. (C) Force direction (ϕ) is defined by clockwise (CW) and counter-clockwise (CCW) rotations relative to the reaching trajectory.

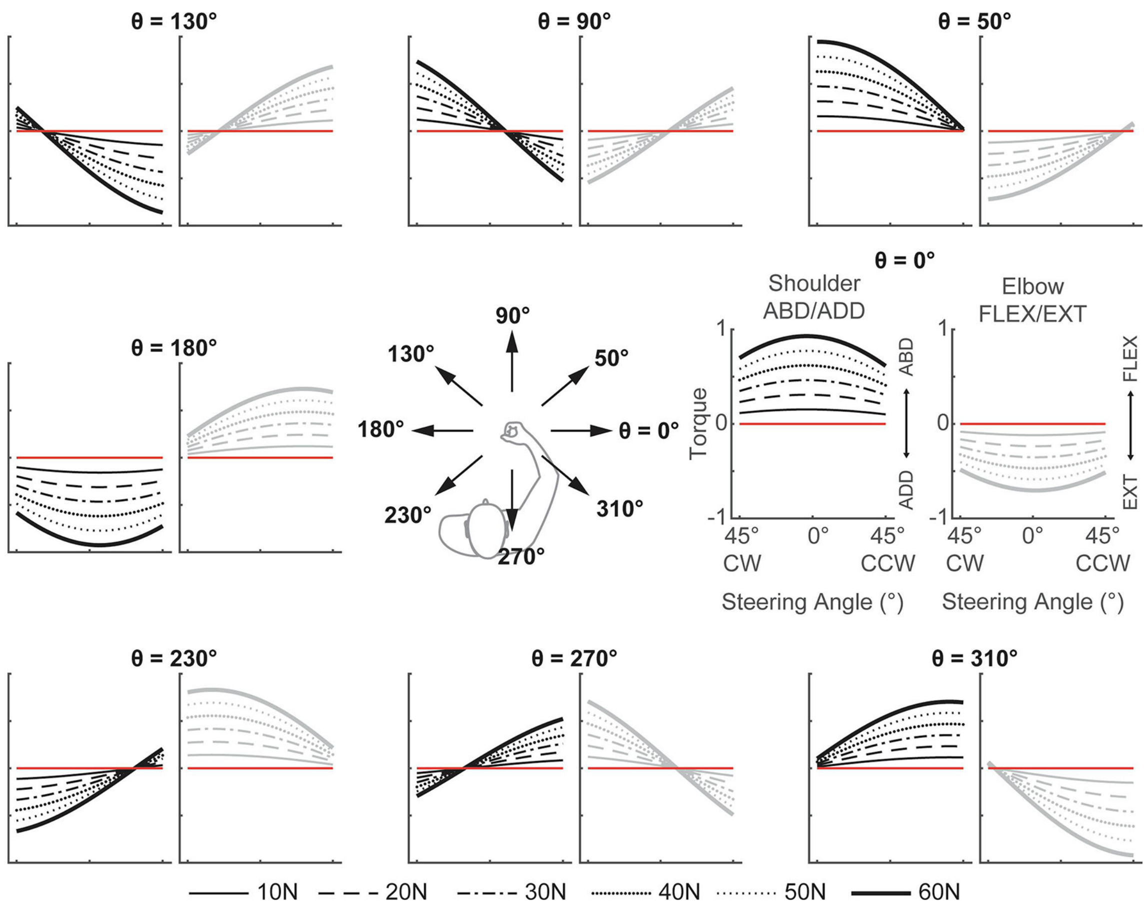

Figure 3:

Average shoulder abduction/adduction and elbow flexion/extension torque for all force conditions during representative reaching directions. The independent axis of each plot is force direction, ranging from 45° CW to 45° CCW, and each trace denotes a different force magnitude. The torques were normalized to the largest recorded torque during all reaches and force conditions. The red line (solid horizontal) denotes zero torque, positive shoulder torque was abduction, and positive elbow torque was flexion.

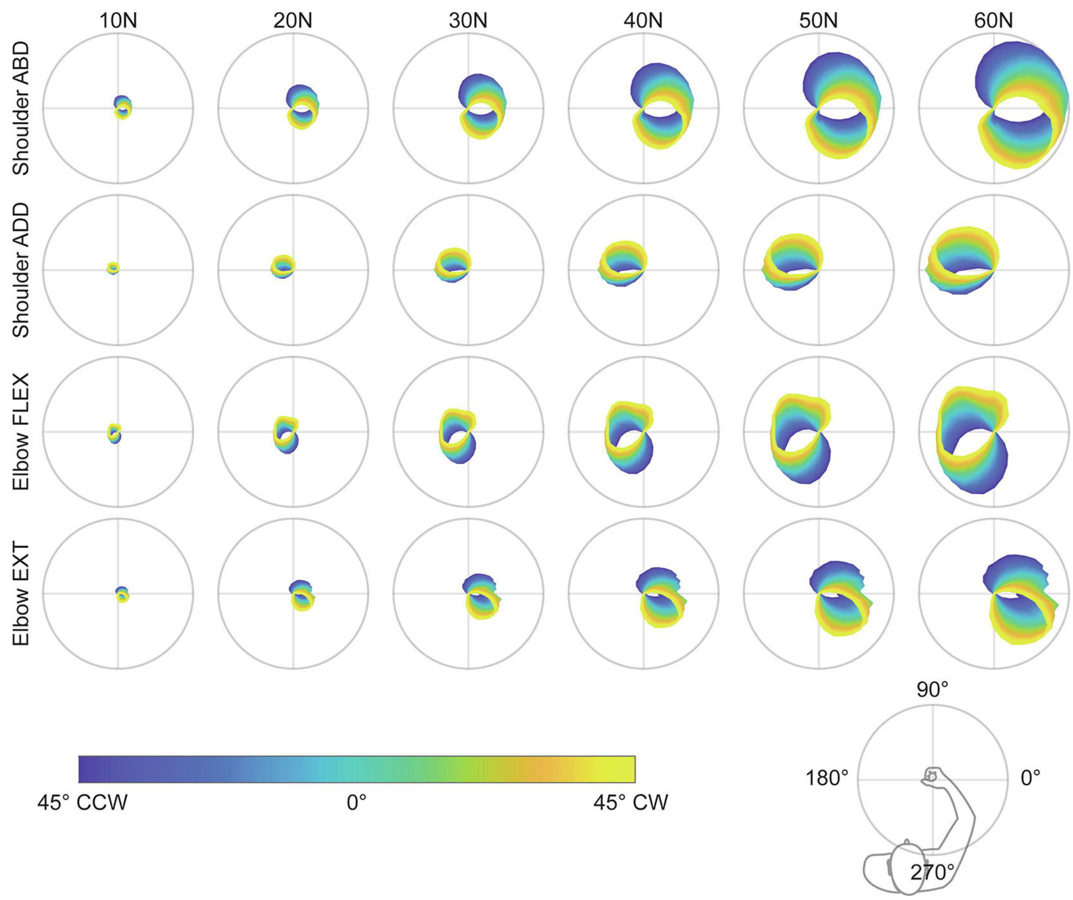

Figure 4:

Shoulder abduction, shoulder adduction, elbow flexion, and elbow extension torque for all force conditions during all reaches. Each trace denotes a different force direction. The outer ring of each polar plot expresses a normalized magnitude of 1.

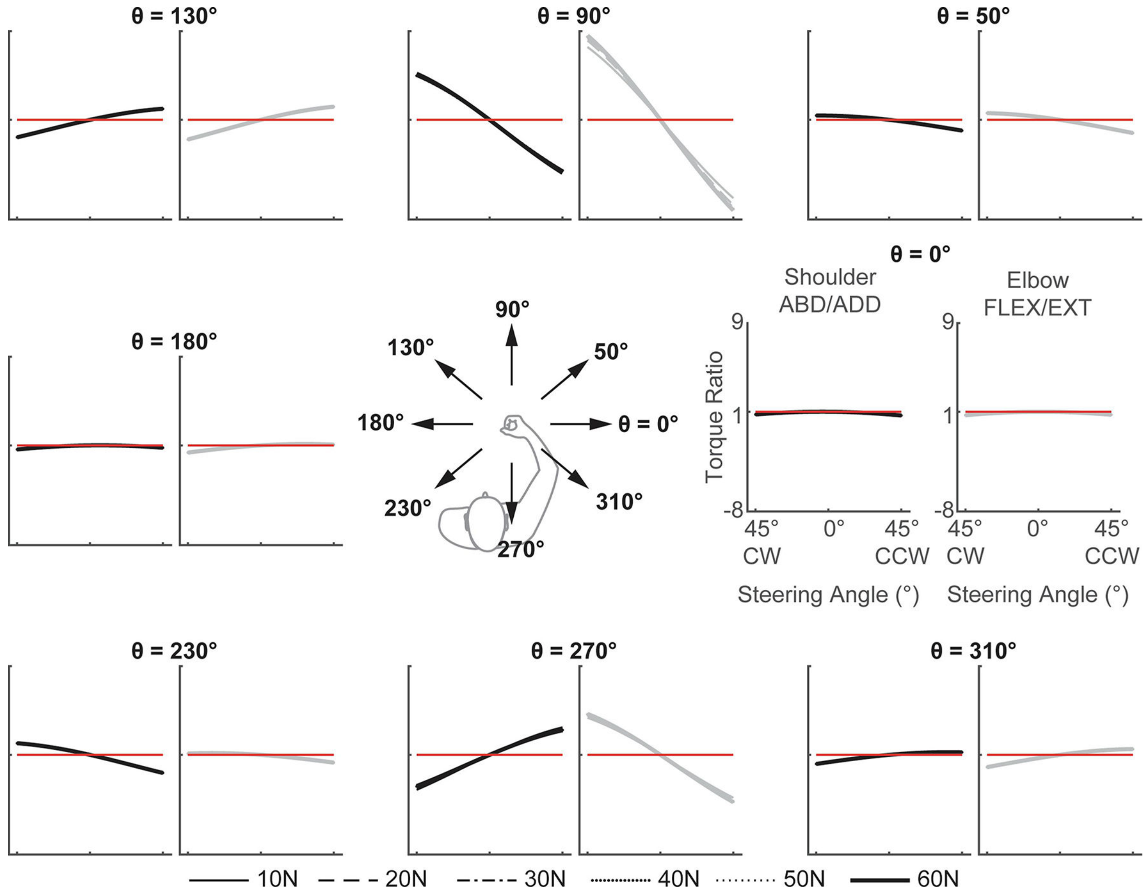

Figure 5:
Torque ratio of shoulder abduction/adduction and elbow flexion/extension for all force conditions during different reaches. A torque ratio of magnitude > 1 means that the force direction caused the torque exerted during the reach to increase relative to the same reach and force magnitude with force direction $\phi = 0°$. A torque ratio < 0 indicates that the direction of the torque exerted during the reach changed direction. The red (solid, horizontal) line denotes a torque ratio of 1, i.e., no change in torque relative to the case when the force direction is 0.

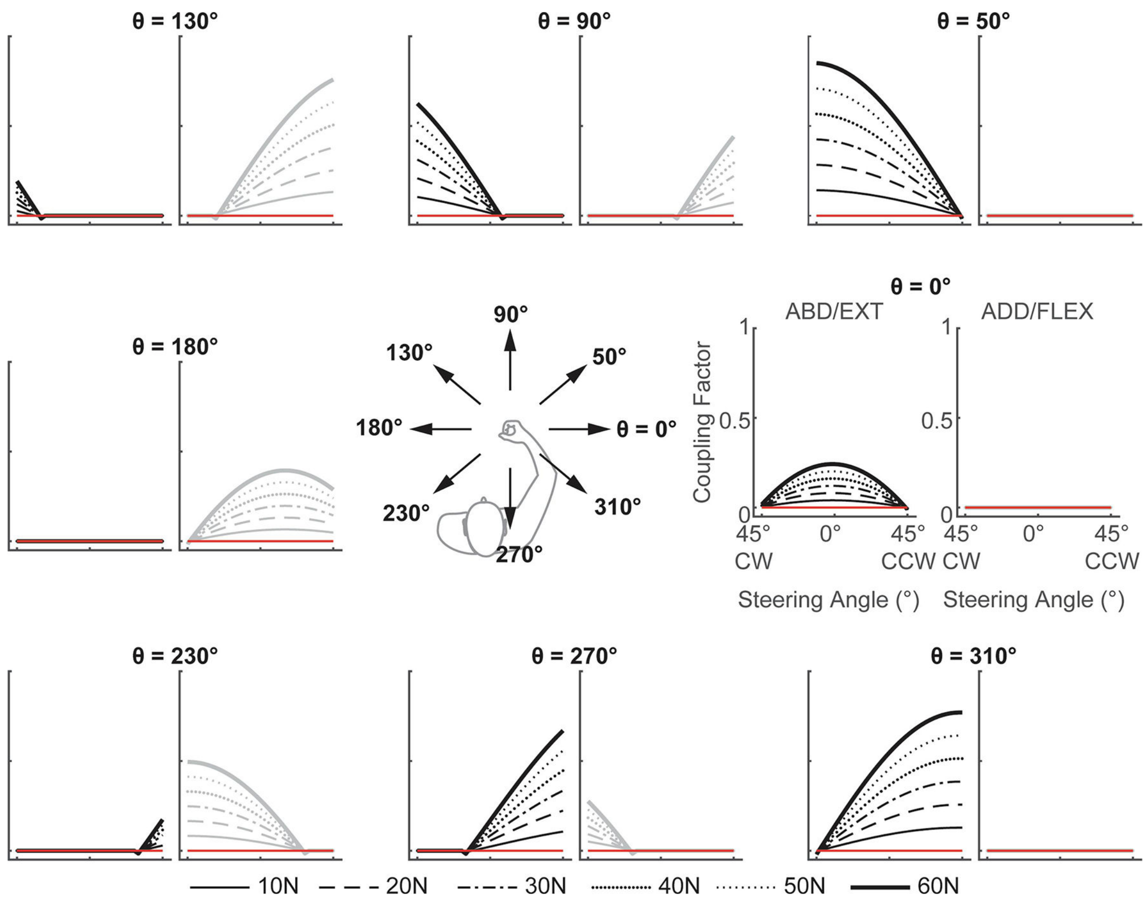

Figure 6:

ABD/EXT and ADD/FLEX coupling factors for all force conditions during different reaches. A reach that achieves a high ABD/EXT coupling factor means that it is a potential candidate for an intervention addressing the flexor synergy. Likewise, a reach that achieves a high ADD/FLEX coupling factor means that it is a potential candidate for an intervention addressing the flexor synergy. The red (solid, horizontal) line denotes a coupling factor of zero.

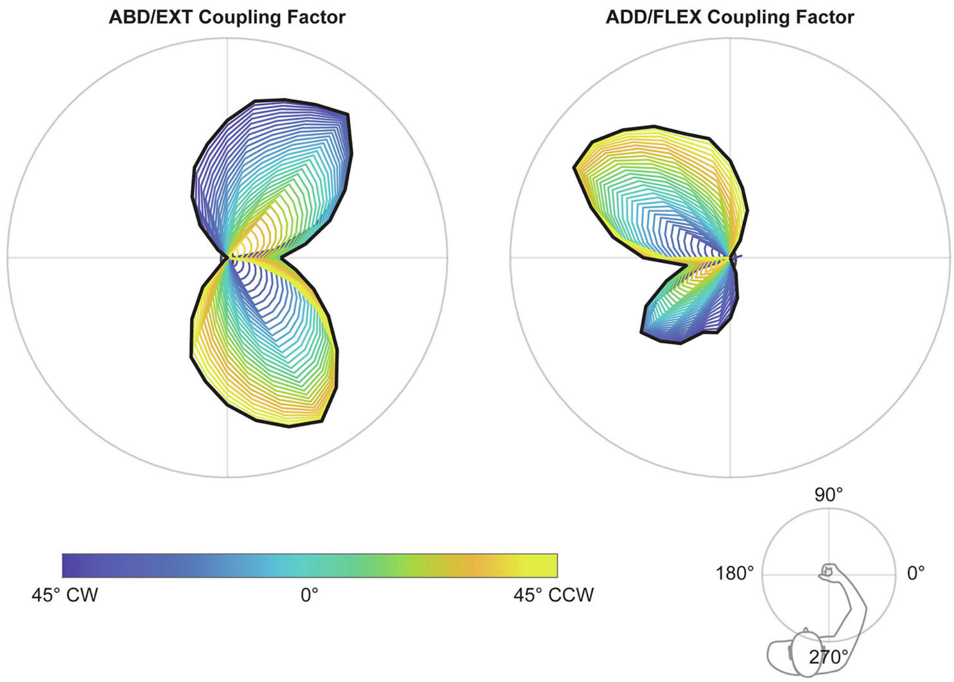

Figure 7:
ABD/EXT and ADD/FLEX coupling factors for all force conditions during all reaches. A reach that achieves a high ABD/EXT coupling factor means that it is a potential candidate for an intervention addressing the flexor synergy. Likewise, a reach that achieves a high ADD/FLEX coupling factor means that it is a potential candidate for an intervention addressing the flexor synergy. Only the 60N force conditions are shown, as magnitude appears to simply amplify the effects of force direction on joint torques. The black curve in each plot denotes the highest coupling factor for each reach.

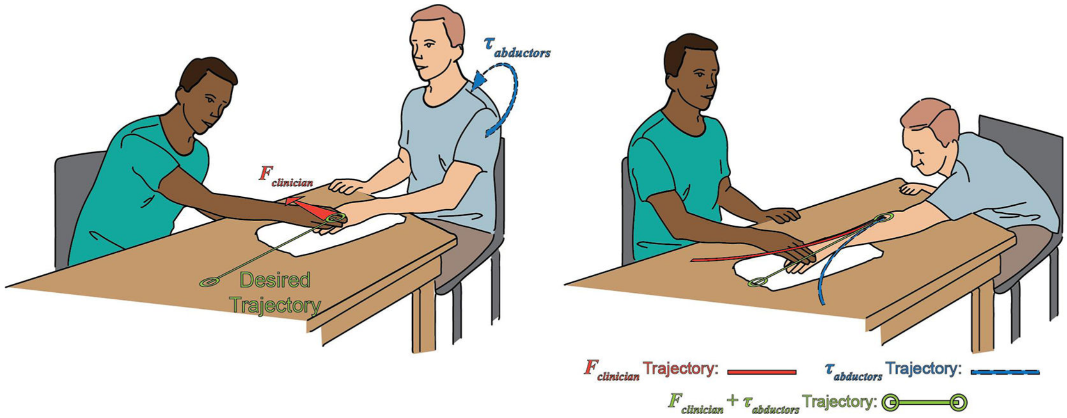

Figure 8:

Visual demonstration of a potential clinical implementation of the findings of this study using towel slide exercise. Left: As a patient (light blue shirt) attempts to slide a towel along a desired trajectory, the clinician (green shirt) pulls the patient's hand off the trajectory. The patient counteracts this perturbance by activating their shoulder abductors. Right: The force from the clinician alone results in the red trajectory, the torque from the shoulder abductors alone results in the blue trajectory. Both simultaneously results in the green (desired) trajectory.