Upper-Limb Discoordination in Hemiparetic Stroke: Implications for Neurorehabilitation

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Clinically, upper-limb discoordination after stroke is evident in the form of stereotypic movement patterns that reflect a loss of independent joint control. These movement abnormalities, in conjunction with our recent quantitative findings under isometric conditions, provide evidence for an impaired capacity to generate certain muscle coactivation patterns in the impaired limb. In this article, we examine the parallels that exist between coordination disturbances observed under isometric and movement conditions. Our results suggest that discoordination in stroke may largely represent a manifestation of additional neural constraints on motor outflow. The neurotherapeutic implications of our findings are discussed. Key words: isometric, joint torque, movement coordination, rehabilitation, stroke

Hemiparetic stroke is accompanied by abnormalities of muscle tone (identified as spastic hypertonia or spasticity), muscle weakness, and disturbances of muscular coordination. Of these abnormalities, spasticity and weakness are the easiest to detect and, accordingly, the most intensely studied (spasticity\textsuperscript{10–13}; weakness\textsuperscript{10–14}). However, in many patients, when these physical signs (spasticity, weakness) are treated effectively or when they resolve spontaneously, motor impairment is still present and severe (e.g., Landau\textsuperscript{15}). Therefore, the primary source of movement dysfunction or global disability in many hemiparetic stroke patients is likely neither spasticity nor muscular weakness, but abnormal movement coordination.

Twitchell\textsuperscript{16} provided the first detailed clinical description of the sequence of motor recovery after stroke. A prominent feature of the recovery process was the emergence of "stereotypic" movements of the impaired upper and lower limbs, characterized by a relatively tight coupling of motion at adjacent joints. It should be noted that this coupling was based on visual observation, rather than kinematic or electromyographic measurements. Brunnstrom\textsuperscript{17} subsequently classified these abnormal stereotypic movement patterns into so-called limb "syner-
gies” that were broadly of either flexor or extensor type. These abnormal synergies have received limited modification or study by other investigators.

The first quantitative evidence of abnormal synergies was provided by the study of the activation of elbow and shoulder muscles as a function of force direction in hemiparetic stroke. This study provided quantitative evidence of a reduced set of muscle coactivation patterns in the impaired upper extremity. The residual muscle activation patterns were found to consist of the coactivation of shoulder abductors with elbow flexors and the coactivation of shoulder adductors with elbow extensors. Subsequent work that measured elbow and shoulder joint torques during maximum voluntary contractions revealed a similar coupling between shoulder abduction–elbow flexion and shoulder adduction–elbow extension torques in the impaired limb of stroke participants and the existence of task-dependent weakness consistent with a limited ability to generate torques outside of the abnormal patterns.

In this article, we demonstrate a potential link between abnormal isometric torque patterns and disturbances in planar arm movements performed with the impaired limb. The implications of these findings are discussed with respect to neurotherapeutic interventions such as the novel strengthening paradigms currently under investigation in our laboratory. Parts of this work have been presented in abstract form.

Method

Isometric Measurements

Six hemiparetic stroke patients and four control subjects participated in our isometric studies. Our stroke patients were mildly to severely impaired as judged by the Fugl-Meyer clinical motor performance scores for the upper limb (see Table 1). Participants produced static elbow and shoulder torques that were measured using a load cell (ATI Industrial Automation, Garner, NC). All participants completed a single-task protocol that measured maximum voluntary torques for the shoulder and elbow degrees of freedom (flexion/extension of the elbow; flexion/extension, abduction/adduction, and external/internal rotation of the shoulder). Both limbs were examined in separate sessions that were spaced approximately 1 week apart. Additionally, two of our stroke patients (PC and NS; see Table 1) completed a multitask protocol that required the simultaneous generation of torques at both joints. These protocols are described in more detail later.

Single-task protocol

During the single-task isometric protocol, maximum voluntary torques (MVTs) were generated in four randomly ordered blocks consisting of elbow flexion and extension, shoulder flexion and extension, shoulder abduction and adduction, and shoulder external and internal rotation. For each trial, torques were recorded for the primary torque direction (i.e., corresponding to the torque that the participant was attempting to maximize) as well as in the three remaining (secondary) degrees of freedom (DOFs). Visual feedback of the primary torque was provided on a computer monitor (see Fig. 1A). Contractions were 2–4 seconds in duration. A minimum of three successive MVTs were performed for each of the eight torque directions with a 1-minute rest peri-
Table 1. Clinical data for the hemiparetic stroke participants

<table>
<thead>
<tr>
<th>Participant</th>
<th>Sex</th>
<th>Age</th>
<th>Hand preference</th>
<th>Lesion site and location</th>
<th>Years since onset</th>
<th>Functional evaluation(^a)</th>
<th>Spasticity(^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MD</td>
<td>F</td>
<td>48</td>
<td>Left</td>
<td>Left frontal cortex</td>
<td>9</td>
<td>56</td>
<td>3</td>
</tr>
<tr>
<td>LL</td>
<td>M</td>
<td>43</td>
<td>Right</td>
<td>Right internal capsule and basal ganglia</td>
<td>8</td>
<td>50</td>
<td>3</td>
</tr>
<tr>
<td>PC(^c)</td>
<td>F</td>
<td>56</td>
<td>Right</td>
<td>Left frontal cortex</td>
<td>5</td>
<td>41</td>
<td>1</td>
</tr>
<tr>
<td>NS(^c)</td>
<td>M</td>
<td>68</td>
<td>Right</td>
<td>Right frontal cortex</td>
<td>6</td>
<td>40</td>
<td>1</td>
</tr>
<tr>
<td>JM</td>
<td>F</td>
<td>36</td>
<td>Right</td>
<td>Right frontal cortex</td>
<td>9</td>
<td>33</td>
<td>3</td>
</tr>
<tr>
<td>LA(^c)</td>
<td>M</td>
<td>45</td>
<td>Right</td>
<td>Right frontal cortex</td>
<td>15</td>
<td>18</td>
<td>3</td>
</tr>
</tbody>
</table>

Note: M = male; F = female.
\(^a\)Based on Fugl-Meyer scale (maximum score = 66).
\(^b\)Modified Ashworth score for the elbow (0 = normal function, 5 = severe spasticity).
\(^c\)Patient participated in the dynamic experiments.

Additional trials were performed if the smallest peak torque for the three trials was less than 85% of the largest peak torque, until no increase in peak torque was observed.

Multitask protocol

The multitask protocol allowed us to identify constraints in the participant’s capacity to generate torques in the shoulder flexion/extension—elbow flexion/extension “plane” (see Fig. 1B) while mimicking the supported and unsupported conditions for arm movements (see dynamic experiments). Focusing on the first quadrant (Fig. 1B, shoulder flexion–elbow flexion), for each trial, the participant was required to generate: (1) maximum shoulder flexion, (2) maximum flexion at the elbow while maintaining maximum shoulder flexion, and (3) maximum elbow flexion while slowly reducing shoulder flexion torque to zero. Visual feedback was provided by the vertical (shoulder torque) and lateral (elbow torque) movement of a cursor on a comput-

Figure 1. (A) Single-task protocol: A dial gauge provided feedback of the torque generated in the primary direction. (B) Multitask protocol: Traces of elbow/shoulder flexion/extension torque combinations generated in each of the four quadrants are shown, with and without shoulder abduction torque. The circular cursor used to provide feedback of the torques is shown at the center of the display. Flexion/extension torques at the shoulder and elbow were indicated by the vertical and lateral movements of the cursor, respectively. For trials requiring control of abduction torque, the participant was asked to maintain the dial within the pie piece on the cursor.
er monitor. Three to five trials were performed. For increased motivation, a trace of the torque path (see Fig. 1B) was left on the screen and updated as the participant's performance improved from trial to trial. The duration of each trial was 10 seconds to ensure that the participant was able to maintain the torque combinations. Trials were also performed with the additional requirement that the participant maintain a shoulder abduction torque equivalent to that required to lift the arm, the cast, and a lightweight arm support piece (equivalent to planar arm movements without passive support; see Fig. 1B, Multi-task + Abduction). The required abduction torque was determined based on estimated mass properties of the limb, adjusted for the mass properties of the arm support and cast. Trials with and without control of the shoulder abduction torque were interchanged to prevent fatigue in the shoulder abductors. This procedure was repeated for each of the four quadrants to yield a complete description of the shoulder–elbow flexion/extension torque plane. Prior to data collection, each participant completed a training session to become familiar with the setup and the multitask protocol.

Analysis of single-task data

For each trial, we identified the maximum torque in the primary DOF by using a 250 ms moving average filter. We used the torques produced in the secondary DOFs at the time of the occurrence of the maximum torque in the primary DOF to characterize the joint torque pattern generated by the participant. MVT for each torque direction was defined as the maximum torque measured across trials. To facilitate comparison of torque patterns across limbs and participants, we normalized secondary torques by the corresponding MVTs.

We performed univariate analyses of variance for the patient and control groups to analyze the dependence of secondary torques in each DOF on limb (impaired/unimpaired or dominant/non-dominant) and primary torque direction (PTD). A two-factor design with repeated measures on both factors was used. Comparisons between the control and patient groups were completed using a two-factor (group, PTD) mixed design with repeated measures on one factor. Pooled data were used for the control group, because statistical analysis revealed no significant differences between the dominant and nondominant limbs. Furthermore, no significant differences were apparent between the pooled control data and the unimpaired upper limbs of stroke patients. Separate analyses were conducted for each of the four DOFs (i.e., elbow flexion/extension, shoulder flexion/extension, shoulder abduction/adduction, shoulder external/internal rotation). The t test was used for the planned post hoc comparisons between group means.

Dynamic measurements

Participants

Our stroke participants were either severely (n = 1) or moderately (n = 2) impaired as determined by Fugl-Meyer scores (see rows for PC, NS, and LA in Table 1) for the upper limb. None of the participants had clinically discernable sensory or cognitive deficits, and all three patients participated in the single-task pro-
tocol described earlier. The two moderately impaired patients also participated in the multitask isometric protocol.

**Movement protocol**

Participants were seated in a chair in front of a table with their torso immobilized by a set of straps and their wrist and finger joints immobilized using a fiberglass cast. Support of the upper limb in a horizontal plane was provided by a balsa wood platform that functioned as a low inertia air bearing (see Fig. 2). In the first set of experiments, the participants performed movements with the arm supported from a central starting point to each of 24 randomly presented targets (indicated by spots of light projected on the table surface) located equidistantly (every 15 degrees) around the circumference of a circle. In a second set of experiments, the participants performed the same protocol without passive support. Movements were performed as rapidly as possible without regard to the fine accuracy of the movement. Eleven consecutive repetitions were performed for each target direction.

**Analysis**

Movement kinematics were recorded using the Optotrak 3010 system (Northern Digital, Inc., Ontario, Canada). The Cartesian positional data were digitally filtered and converted into joint angles (inverse kinematics). End-point and angular velocities and accelerations were determined using numerical differentiation. The flexion(+)/extension(-) joint torques at the shoulder and elbow were estimated using the inverse dynamics equations for a two-link system (for details, see Beer et al.20).

![Figure 2. Experimental setup for supported and unsupported arm movements.](image)

**Results**

**Isometric findings**

**Single-task isometric protocol**

The torque patterns associated with the generation of MVTs in each of the eight directions are summarized in Figure 3 (group results, n = 6). The results show that significant (non-zero, based on t test) secondary torques were normally present in at least one DOF for the unimpaired upper limb. Similar patterns were also observed in either limb of the four control participants. For example, during performance of maximum shoulder abduction (AB), torques were generated concurrently in elbow flexion (EF) and shoulder flexion (SF). As summarized in Figure 3 (right panel), significant differences were found between the torque patterns exhibited by the impaired limb and those associated with the unimpaired limb and the control group. With reference to Figure 3 (middle panel), these differences generally involved an abnormal “coupling” among torques in the sets {EF,
Figure 3. Torque patterns associated with the generation of maximum voluntary torques in stroke participants ($n = 6$). Left panel, unimpaired limb; middle panel, impaired limb. Gray scale indicates normalized torque magnitude (ratio of secondary torque magnitude and corresponding maximum voluntary torque). Significant secondary torques are in the positive direction (elbow flexion, shoulder abduction, shoulder flexion, shoulder external rotation) unless indicated otherwise. Right panel, summary of statistically significant interlimb differences in normalized secondary torques based on comparison of the impaired and unimpaired limbs. EF = elbow flexion; EE = elbow extension; SF = shoulder flexion; SE = shoulder extension; AB = shoulder abduction; AD = shoulder adduction; ER = shoulder external rotation; IR = shoulder internal rotation.

AB, ER, SE} and {EE, AD, IR} and, hence, closely parallel the abnormal muscle coactivation patterns reported previously.\textsuperscript{18}

**Multitask protocol**

Figure 4 compares torque envelopes with ("unsupported") and without ("supported") a concurrent shoulder abduction torque for one of our participants. Results for both moderately impaired stroke participants were similar. As evidenced by Figure 4, both participants exhibited substantial decreases in maximum elbow extension, shoulder flexion, and shoulder extension torques when they were required to generate abduction torque. These results confirm and extend our previous findings of an abnormal decrease in maximum voluntary

Figure 4. Smoothed envelopes of maximum voluntary torques in the shoulder/elbow–flexion/extension torque plane. The envelopes were determined by finding the outer boundary of all trails.
elbow extension torque in the impaired limb under conditions requiring control of
the shoulder abduction torque.\textsuperscript{20}

\textbf{Dynamic findings}

\textit{Degradation of dynamic torques during unsupported arm movements: Single reaching direction}

The functional impact of the task-dependent elbow weakness is strikingly demonstrated by considering the results for a severely impaired participant (Fugl-Meyer score 18/66). Trajectories for supported and unsupported reaching movements performed with the impaired upper limb are compared in Figure 5. For the sake of clarity, only 3 of 11 trials are shown with a mean vector that estimates the direction of the initial trajectory. For this particular patient, the abduction/external rotation torque required for support of the limb represented only 30\% of maximum. However, as would be predicted based on our published results under static conditions,\textsuperscript{18,20} a

\textbf{Figure 5.} Comparison of actively and passively supported reaching movements performed with the impaired limb for a stroke patient with severe functional impairment. (A) Hand paths for supported and unsupported reaching movements. (B) Hand tangential velocity profiles. Three trials are shown for each support condition. (C) Shoulder flexion and elbow extension joint torques derived from inverse dynamic calculations for supported and unsupported arm movements for the same target direction (mean of 10 trials). Note the absence of elbow extension torque in the unsupported case.
gross deterioration in the direction (Fig. 5A) and velocity (Fig. 5B) of movement is apparent in the actively supported condition in reflection of this participant's limited ability to generate elbow extension and shoulder abduction/external rotation torques simultaneously. This is further substantiated in Figure 5C; joint torque estimates from an inverse dynamics analysis demonstrate a lack of elbow extension torque during unsupported reaching movements. Also noteworthy is the relatively preserved ability of this severely impaired patient to initiate supported reaching movements (although the terminal phase remains abnormal due to a stoppage of elbow motion, perhaps reflecting spasticity of the elbow flexors).

Degradation of dynamic torques during unsupported arm movements: Multiple directions

To demonstrate the effect of task-dependent elbow weakness on the planar workspace, we compared hand paths for movements performed with and without passive support to each of 24 targets spaced equidistantly around the circumference of a circle. Representative results for the moderately impaired participants are shown in Figure 6. Relative to the supported condition, in the unsupported condition a reduction in the planar workspace was apparent for reaching movements (i.e., movements away from the body), while the ability to acquire targets near the body was preserved. The severely impaired participant could no longer initiate any reaching movements as shown in Figure 5.

To characterize the differences between dynamic torques for the supported and unsupported conditions, we plotted the shoulder and elbow torques against each other for each movement to yield a torque “trajectory.” Figure 7 summarizes torque trajectories for the initiation phase of movements toward each of the 24 targets for the moderately impaired participant discussed in the static multitask experiments (see Fig.

![Supported and Unsupported Movements](image-url)

**Figure 6.** A significant reduction in work area can be observed in this moderately impaired participant for all “reaching” directions requiring a combination of shoulder abduction and elbow extension torques (see unsupported plot).
4). A degradation in dynamic elbow extension torque during unsupported arm movements is clearly evident (compare left and right panels of Fig. 7, second and third quadrants), while elbow flexion torque generation is largely preserved. When we compare the degradation in dynamic torques with the degradation in static torques (see Fig. 4), we observe reduced torques in the same quadrants.

Discussion

Our results demonstrate similar constraints in the generation of joint torque patterns during isometric and actively supported reaching movements in the impaired upper limb. Specifically, the reduction in the participants’ ability to generate elbow extension torques while exerting shoulder abduction torques parallels our earlier observations in stroke.19,20 The effect of these apparent torque constraints is a possible reduction in work area and a significant reduction in peak movement velocity. Reductions in available work area and peak velocity are especially noticeable in participants with moderate to severe impairments in the upper limb. The clinical implications of these findings with respect to the developments of novel therapeutic interventions will be addressed in subsequent sections.

Clinical Implications

Current neurotherapeutic approaches for the treatment of upper-limb dysfunction after stroke

Current neurorehabilitation techniques17,27,28 that attempt to facilitate functional recovery in the upper limb after stroke are highly variable in treatment philosophy and have generally met with limited success. This apparent lack of success may be related to multiple factors, including the type and intensity of treatment, patient selection criteria, and the use of
qualitative low-resolution scales of measurement to assess recovery. More focused, high-intensity therapies for the treatment of upper-limb dysfunction stroke have been developed and studied over the last 15 years with evidence of improved motor recovery. Although these results are very encouraging, none of these approaches are based on quantitative measurements of the patient’s motor deficits.

**Computer-assisted quantifiable measurement and training tools**

The current study provides not only a quantitative measure of coordination disturbances in the impaired arm but also the framework for the development of novel computer-controlled rehabilitation programs. We are currently evaluating the efficacy of a computer-assisted isometric strength training protocol for enhancing reaching movements in chronic stroke patients. The training protocol requires the patient to generate specific combinations of shoulder and elbow torques, with a particular focus on the torque patterns required for reaching movements. The software that we have developed provides stimulating feedback to the patient to facilitate performance of the multiple repetitions required to master the joint torque combinations.

An advantage of the isometric protocol is that training of even very impaired participants is possible because no minimum level of functional ability is required. The computer-controlled static paradigm can be tailored to meet the individual patient’s initial functional level and is also adaptable to the patient’s recovery process. Our results to date suggest that chronic stroke participants can increase their capacity to generate torques outside of the abnormal patterns over the course of an 8-week training sequence. The effects of training-induced reductions in isometric torque constraints on reaching movements are currently under investigation.

**Implications for the use of functional electrical stimulation (FES) in the impaired upper limb after stroke**

The determination of constraints in the patients’ ability to generate the joint torque patterns necessary for functional arm movements also has important implications for the design of FES equipment for stroke participants. For instance, task-dependent constraints that are observed in the impaired upper extremity of stroke participants could be addressed using an EMG-driven electrical stimulator. Such a “smart” stimulator could be designed to activate the triceps brachii muscle(s) depending on the activation patterns of shoulder muscles. The result would be a stimulation-induced activation of the triceps to overcome biceps activity that occurs when certain shoulder abduction/flexion muscles are coactivated as during the onset of a reaching movement. In addition to overcoming biceps activity, beneficial effects of FES may include reciprocal inhibition of elbow flexors and an increased incentive for stroke participants to use their impaired arm.

In conclusion, an enhanced understanding of the relationship between abnormal constraints on torque generation in the impaired limb and discoordination of voluntary movement may lead to the development of more effective neurorehabilitative interventions. The use of strengthening techniques, FES, or sensory stimulation that
promote the use of joint torques outside of the abnormal torque constraints manifested in the hemiparetic arm\(^9\) should be strongly considered in the design of novel interventions for treatment of the impaired upper limb after stroke.

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