Gains in Upper Extremity Function After Stroke via Recovery or Compensation: Potential Differential Effects on Amount of Real-World Limb Use

Peter S. Lum, Sara Mulroy, Richard L. Amdur, Philip Requejo, Boris I. Prilutsky, and Alexander W. Dromerick

In terms of integration of the paretic upper extremity in activities of daily living (ADLs), outcome is poor after stroke. Furthermore, amount of real-world arm use appears only weakly correlated with laboratory motor function scales. Therefore, amount of arm use may depend critically on the location, extent, and type of functional gains, which can be quantified with comprehensive kinematic and EMG analysis of ADL performance. Gains in upper extremity function can occur via compensation or recovery of premorbid movement and EMG patterns, and traditional treatment approaches encourage adoption of compensatory strategies early in the postacute period that can inhibit potential recovery. A new treatment approach called Accelerated Skill Acquisition Program (ASAP) focuses on impairment reduction coupled with repetitive, task-specific training of the paretic arm during ADLs. We present pilot data that show recovery in subjects who received the ASAP, while a usual care control subject showed increased use of compensation over the same period. Finally, we discuss the advantages of data reduction methods such as principal components analysis, confirmatory factor analysis, and structural equation modeling, which can potentially distill large kinematic and EMG data sets into the key latent variables that predict amount of real-world use. Key words: compensation, EMG, function, kinematics, recovery, stroke, upper extremity

Stoke is the most common cause of chronic disability for adults in the United States. Despite the natural spontaneous recovery period, chronic residual impairments in both the contralesional upper and lower extremities are present in the majority of individuals. The long-term disability following stroke leaves the majority of survivors with limited use of their hemiplegic arm, with some studies reporting that a full 65% of individuals after stroke are unable to incorporate the hemiparetic upper extremity into daily function. Even mild impairment of upper extremity function after stroke results in significant limitations in daily function and has...
been demonstrated to negatively impact health-related quality of life.\textsuperscript{7,8} A group of patients who were deemed fully recovered after stroke did not integrate the paretic hand into activities of daily living (ADLs), which limited independence and was associated with reduced community participation.\textsuperscript{7}

Reintegration of the contralesional arm into ADLs may be critically dependent on the type of functional gains. Improvement in functional performance after stroke can result from compensatory adaptations to the neurological insult and associated residual deficits, as well as from recovery of normative movement and muscle activation patterns.\textsuperscript{9–13} The goal of rehabilitation is to facilitate both processes of compensation and neurological recovery to maximize the patient's functional outcome. Traditional treatment approaches unfortunately have demonstrated minimal success in restoring useful function of the hemiplegic upper extremity, particularly for those individuals with moderate to severe residual paresis of the hand.\textsuperscript{14} This may be caused in part by an overemphasis on teaching of compensatory strategies, which typically produce more rapid gains in function but may ultimately impede recovery of normal behavior. If this is correct, it becomes critical to employ methods that can distinguish compensatory adaptations from recovery.

To distinguish compensation from recovery, comprehensive kinematic and electromyographic (EMG) analysis is needed to identify the biomechanical underpinnings of improvement in upper extremity function after intervention and to determine the specific movement substrates that predict amount of use of the arm at home. Our operational definition of recovery is normalization of movement smoothness, interjoint coordination, active range of motion (ROM), and normalized muscle activation patterns. Compensation is defined as changes in these variables away from normal levels, as measured in age-matched controls. We define four basic components of arm function (reach, object grasp, object transport, object release) and propose that kinematics and EMG should be evaluated in tasks that incorporate some or all of these components. These data would allow quantification of functional gains in terms of compensation or recovery.

The combination of these data and measures of the amount of arm use at home (portable accelerometry,\textsuperscript{15} Motor Activity Log\textsuperscript{16}) would answer critical questions as to the amount and type of functional gain that best promotes carryover to the home environment. We predict that while both recovery and learned compensatory techniques produce gains in motor functional ability as measured by clinical laboratory scales, reliance on compensation results in far less use of the arm at home because compensation strategies are too awkward, fatiguing, effortful, and limiting to carry over into the home environment. It will also be possible to identify which aspects of arm recovery best predict significant arm use at home and in terms of specific biomechanical and EMG measures. For example, regaining a certain level of supination ability may greatly impact home use, while increasing movement smoothness may have relatively little impact. Identifying which combinations of impairment reductions best predict use of the arm at home would provide invaluable information on how to focus patient treatment using an evidence-based approach.

In this light, new treatment approaches are emphasizing impairment reduction and restoration of normal motion patterns through massed, task-specific practice instead of the traditional emphasis on functional ability. These new approaches are likely to produce more recovery and less reliance on compensatory strategies. One of these approaches is the Accelerated Skill Acquisition Program (ASAP). ASAP is currently undergoing a multisite, phase III, randomized clinical trial titled Interdisciplinary Comprehensive Arm Rehabilitation Evaluation (I-CARE; PI: Winstein). ASAP was developed as a hybrid combination of constraint-induced therapy\textsuperscript{17,18} and skill-based/impairment-mitigating motor learning training with embedded motivational enhancements.\textsuperscript{19,20}

In the following sections, we review the growing evidence that traditional interventions that promote gains in function via compensation may not be the most effective path toward promoting use of the arm outside of the laboratory. Clinical, kinematic, and EMG data from stroke subjects who have received the ASAP intervention are presented, and we discuss several potentially powerful data reduction methods for handling the large
amount of kinematic and EMG data required to quantify performance of complex ADL tasks.

Background

Effects of stroke on reaching and grasping ability

Reaching and grasping objects is a component of many daily activities that require use of the upper extremity. At the shoulder-elbow, post-stroke impairments include decreased muscle activation and weakness, abnormal neural synergies between shoulder and elbow muscles that limit range of motion, disrupted interjoint coordination, decreased smoothness of movement, and dyssynchrony between reach and grasp movements. Grasp impairments include increased tone in finger flexors, impaired voluntary activation of both the extensors and flexors of the fingers, and inability to independently activate muscle groups resulting in coactivation of antagonistic pairs and reduced active range of motion. In general, biomechanical and EMG studies have proven invaluable in objectively quantifying impairments after stroke.

Functional improvement of the paretic upper limb is mainly determined by improvement of the paretic hand, yet restoration of hand function after stroke often lags behind restoration of more proximal joints, and impairments are often resistant to therapeutic intervention. Thirty-eight percent of stroke survivors reported that impaired hand function is the most disabling motor impairment they face. This is consistent with a recent study that reported that reach efficiency (defined as directness of movement), though poor initially, improves by 3 months post-stroke while decreased efficiency of grasp persists up to 1 year. This discrepancy was attributed to use of compensatory strategies in the more proximal musculature of the upper extremity but not in the distal musculature.

Function vs. amount of home use

The relationship between arm motor performance as seen in the laboratory and actual arm use at home is poorly understood. It has been recognized that many stroke patients, when observed in the laboratory, can appear to use the paretic arm with adequate ability yet do not use the arm at home with the expected regularity. This was best demonstrated in a study that found that, at 90 days after stroke, excellent restoration of function as measured by clinical scales (Action Research Arm Test [ARA], Wolf Motor Function Test [WMFT]) did not equal restoration of everyday productive use of the paretic arm in the Motor Arm Log (MAL). For example, correlation between the WMFT functional ability score and the MAL amount of use (AOU) was poor ($r = 0.40$), and correlation between the WMFT movement time score and the MAL AOU was nonexistent ($r = 0.007$). Of the subjects with perfect or near-perfect scores on the WMFT functional ability score (>4.8), only 36% had perfect scores on the MAL. More than half of these subjects reported not using the arm to take off their shoes or put a key in a door, despite having near-perfect functional ability as measured in the laboratory. A similar result was found in a study of constraint-induced movement therapy (CIMT) in chronic stroke. In this study, 56 subjects received intensive therapy for 2 weeks and were evaluated pre and post training with the ARA and the MAL. The correlation between change on the MAL and change on the ARA over the treatment period was weak and not statistically significant ($r = 0.16$), despite the fact that significant gains were seen in the MAL. In addition, recent systematic reviews of experimental interventions have found significant improvement in motor function scales, without change in ADL.

As a result, there has been a call for studies that provide a better understanding of the neurophysiological and biomechanical changes that underlie learning of functional tasks after stroke. Future research will benefit from using quantitative methods to characterize the motor impairment after stroke and then using this information to devise more physiologically based rehabilitation techniques. One approach that appears promising is the use of kinematic analysis of movement patterns that can differentiate between recovery and improvements due to compensation strategies. Understanding movement patterns in these terms has both scientific and clinical significance. In a randomized controlled trial (RCT) of 66 chronic stroke subjects comparing CIMT and
controlled trial, 30 chronic stroke subjects received repetitive training of reach-to-grasp tasks either with or without trunk restraint.77 In a subgroup analysis of moderately impaired subjects, use of trunk restraint resulted in significant gains in active range of motion (reduced trunk movement, increased elbow extension) that were correlated with gains in arm function. In contrast, subjects who received no trunk restraint showed an increased reliance on compensatory strategies after training (increased trunk displacement and less elbow extension). Both groups improved on the Fugl-Meyer (FM)78 assessment of motor function, but significantly larger gains were present in the trunk restraint group. In another study from this laboratory, chronic stroke subjects who practiced targeted reaching movements with explicit verbal instructions to extend the elbow and flex the shoulder showed increased joint range, better interjoint coordination, decreased compensation (trunk rotation), and improved arm function.79 No recovery was found in subjects who performed the same training but only received knowledge of results in the form of final endpoint error. Once again, these authors concluded that compensations may improve motor function in the short term, but use of atypical movement kinematics can limit use of the limb at home and eventually be associated with discomfort and joint contractures.

These results are consistent with the work of Dewald and colleagues who showed the presence of abnormal neural synergies between shoulder abduction and elbow flexion that inhibited the ability to simultaneously abduct the shoulder and extend the elbow.31,32 This impairment can be overcome with compensatory strategies (excessive trunk movement), but recovery is possible with a focused intervention.80 Three times a week for 8 weeks, chronic stroke subjects practiced generation of simultaneous shoulder abduction and elbow extension isometric torque, with the help of real-time feedback of the torques produced and desired target levels. Restoration of normative coordination patterns was observed after training.

The concept that compensatory strategies can mask more normal movement patterns has been elegantly demonstrated by the work of Levin and colleagues.76 They showed that in a single session, when the trunk is restrained, reaching patterns in the shoulder and elbow improve toward normative performance. In a subsequent randomized dose-matched bimanual neuro-developmental treatment (NDT), significantly larger gains in the CIMT group was seen in the ARA and MAL after training73; however, the advantage for CIMT in terms of amount of home use (MAL) was lost at the 1-year follow-up. The authors speculated that this was attributable to the fact that the gains in the ARA were due to compensation and not recovery. They could only speculate because they had no quantitative data on movement patterns. Clearly, a comprehensive study is required that will provide detailed kinematic and EMG data and objective data on amount of arm use at home.

Compensation vs. recovery

Recovery can be thought of as restoration of normal movement kinematics and muscle activation patterns, while compensation is the use of alternative degrees of freedom (DOFs) and/or muscles to complete the task. For example, trunk and proximal arm DOFs are recruited to compensate for distal arm impairments in orienting the hand during reach-to-grasp tasks.74 Traditionally, teaching of compensatory strategies is considered appropriate when recovery is deemed unlikely. However, adoption of compensatory strategies in the acute and subacute phases of stroke may limit long-term recovery.19 This was illustrated by the study of Roby-Brami and colleagues that involved longitudinal measures of kinematics every 4 weeks starting from the subacute stage.75 Two distinct paths to functional gain emerged: recovery of normal patterns and development of compensatory strategies. In both cases, the patterns strengthened with time and improved motor performance was observed; however, the subjects with recovery had the greatest gains of function in the long term. Thus, therapies that promote compensation may permit short-term gains in motor performance in the laboratory setting but may be detrimental in the long term.

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The impact of therapeutic intervention on reaching and grasping functions likely depends on the initial level of severity. Thielman et al compared two treatment approaches for improving reaching function in the chronic poststroke
phase—task-related training (TRT) and progressive resistance exercises (PRE). The largest effects were increased trunk compensation and straighter hand paths in the low functioning subjects after TRT and reduced trunk compensation in the high functioning subjects after PRE. This suggests that mildly impaired reaching function requires strengthening exercise (recovery) to restore function and that a more severe functional deficit in reaching is restored primarily by compensation that is facilitated by practice rather than strengthening. However recent work suggests that dynamic multijoint strengthening approaches are effective in severe stroke.

Case Studies: Change in Upper Extremity Biomechanics in Response to the ASAP

The purpose of this pilot study was to demonstrate the effect of the ASAP compared to usual and customary care on recovery and compensation as revealed by the kinematics and muscle activity during reach and grasp tasks in individuals with mild and moderate initial upper extremity (UE) impairment following stroke.

Subjects

Four individuals 1 to 3 months post stroke with persistent UE hemiparesis resulting in impaired arm function at the time of the initial assessment participated. All subjects had at least minimal active finger extension of the involved hand, mild to moderate upper extremity paresis as evidenced by a UE Fugl-Meyer score of 31–58, and preserved cognitive function as determined by the Mini-Cog.

Methods

Two subjects underwent the ASAP training protocol at Rancho Los Amigos National Rehabilitation Center and a third subject received training using the ASAP protocol at Emory University in Atlanta. A fourth subject served as the “usual and customary care” (UCC) control and only received the pre- and posttreatment testing. No actual treatment of the arm was provided to the UCC. For comparison, three subjects with no UE impairments served as nondisabled control (NC). The three intervention subjects (ASAP) received 30 hours of ASAP training: 2 to 3 hours/session, 3 days/week, for 4 to 5 weeks. The functional training, chosen in collaboration with each subject, was aimed to improve strength, fine motor control, and bimanual use of the more involved UE. The training session began with collaborative ordering of the real-world training tasks identified during orientation. The real-world tasks could change as interests and goals evolved, however the priority task was not allowed to change. Task and movement analysis was done for each real-world task to determine the key movement dysfunctions or impairments. The goal of intervention training was to focus attention and effort directly on the problematic area (i.e., dysfunction, impairment) to facilitate skill acquisition without simply providing a compensatory strategy as a quick fix to the problem. Classic physiologic-like overload parameters were used to drive progress. Practice activities within the real-world tasks were selected based on patient perspective/preference. Training was collaborative and interactive with the patient actively participating in problem solving and assessing performance. Confidence building and empowerment were embedded in the training and education including self-efficacy assessment and interactive problem-solving. Subjects designed intersession practice activities for the home and community settings.

UE kinematics (MiniBirds®; Ascension Technology Corporation, Milton, Vermont) and EMG were recorded (pre and post intervention) while subjects performed tasks including reach, grasp, and transport of a dowel to a target and reach, grasp, and drink (simulated) from a water bottle with the more involved arm. The electromagnetic markers were placed at the first thoracic vertebrae spinous process, the lateral aspect of the brachium, distal dorsal aspect of the antebrachium, dorsum of the hand at the base of the third metacarpal, thumb nail, and index finger nail. These sensors recorded body segment and finger movements in three-dimensional space (three translations and three rotations) with a sampling rate of 120 Hz. The start and stop times of the reach and transport phases were determined from event triggers (Figure 1). The recorded raw linear and angular displacements of the electromagnetic markers
were low-pass filtered with a fourth order, zero lag Butterworth digital filter. Using commercially available software (Motion Monitor®, Innovative Sports Training, Chicago, Illinois), these sensor data were then converted into the displacements of the centers of rotation of the glenohumeral, elbow, and wrist joints. Also calculated are the joint angles at the glenohumeral joint (flexion/extension, abduction/adduction, internal/external rotation), elbow joint (flexion/extension, supination/pronation), and wrist joint (flexion/extension). The grasp aperture was calculated as the distance between the markers on the thumb and index finger. The smoothed linear and angular displacement data were differentiated using central difference algorithms to determine both velocity and acceleration curves.

Smoothness of task performance was quantified using the number of times the tangential acceleration profile of the hand path crossed zero. Interjoint coordination was calculated using the correlation coefficient of the phase plot of two joint angles over an entire movement. If the two joints begin and end rotation synchronously and maintain a fixed ratio of angular velocities, the correlation coefficient will be unity. If the ratio of angular velocities varies over the course of the movement, the coefficient will be less than unity. This method has been used effectively to differentiate normal from impaired temporal interjoint coordination during reach and point activities⁸³ and reach and drink from a glass motions.⁸⁴ Distal interjoint coordination was represented by the correlation between aperture and elbow extension during the reach phase. Proximal interjoint coordination was represented by the correlation of elbow flexion and shoulder abduction during the hand to mouth portion of the transport phase of the water bottle task.

EMG activity was recorded in all subjects tested at Rancho Los Amigos National Rehabilitation Center. Indwelling bipolar, 50 µm Ni-Cr alloy fine-wire electrodes were inserted into four wrist and finger muscles in the involved arm including extensor digitorum communis (EDC), extensor carpi radialis (ECR), flexor carpi radialis (FCR), and flexor digitorum profundus (FDP). EMG amplitude during maximal voluntary contraction (MVC) was full-wave rectified and integrated over 0.02-second intervals. A moving window located the greatest 1 second of EMG amplitude during the 5-second MVC. The average EMG amplitude during this maximum 1 second served as the normalization value (100%MVC) for movement trials.
Table 1. Upper extremity (UE) functional test scores and kinematic parameters during reaching and grasping before and after Accelerated Skill Acquisition Program (ASAP) and usual care

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Usual care control</th>
<th>ASAP-1 Emory</th>
<th>ASAP-2 RLA</th>
<th>ASAP-3 RLA</th>
<th>Able-bodied mean of 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>UE Fugl-Meyer</td>
<td>58</td>
<td>42</td>
<td>37</td>
<td>31</td>
<td></td>
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<td>WMFT, seconds (average movement time)</td>
<td>pre 1.55</td>
<td>5.95</td>
<td>7.44</td>
<td>11.79</td>
<td></td>
</tr>
<tr>
<td></td>
<td>post 2.81</td>
<td>4.53</td>
<td>5.38</td>
<td>6.57</td>
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<td>WMFT (functional ability)</td>
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<td>NA</td>
<td>3.0</td>
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<td></td>
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<tr>
<td></td>
<td>post 4.1</td>
<td>NA</td>
<td>3.32</td>
<td>3.6</td>
<td></td>
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<tr>
<td>Stroke Impact Scale (upper extremity raw score)</td>
<td>pre 16</td>
<td>8</td>
<td>12</td>
<td>6</td>
<td></td>
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<tr>
<td></td>
<td>post 25</td>
<td>NA</td>
<td>19</td>
<td>18</td>
<td></td>
</tr>
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<td>Reach time, seconds</td>
<td>pre 1.0</td>
<td>1.75</td>
<td>2.38</td>
<td>2.63</td>
<td>0.49</td>
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<td>Dowel Power Same (palm down)</td>
<td>post 1.26</td>
<td>0.98</td>
<td>1.43</td>
<td>1.42</td>
<td></td>
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<tr>
<td>Extent</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>Aperture, cm</td>
<td>pre 12.2</td>
<td>11.6</td>
<td>10.1</td>
<td>10.5</td>
<td>12.8</td>
</tr>
<tr>
<td></td>
<td>post 10.8</td>
<td>14.5</td>
<td>11.6</td>
<td>13.7</td>
<td></td>
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<tr>
<td>Water bottle</td>
<td>pre 15.9</td>
<td>35</td>
<td>12.7</td>
<td>0</td>
<td>28.4</td>
</tr>
<tr>
<td></td>
<td>post 22.2</td>
<td>39</td>
<td>39.1</td>
<td>8.0</td>
<td></td>
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<td>Wrist extension, degree</td>
<td>pre 109</td>
<td>97</td>
<td>88</td>
<td>92</td>
<td>54</td>
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<td>Elbow extension (deg, full ext=0 deg)</td>
<td>post 94</td>
<td>92</td>
<td>75</td>
<td>89</td>
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<tr>
<td>Dowel Power Same (palm down)</td>
<td>post 71</td>
<td>58</td>
<td>129</td>
<td>91</td>
<td>43</td>
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<td>Shoulder abduction, degree</td>
<td>post 101</td>
<td>53</td>
<td>69</td>
<td>74</td>
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<td>Reach phase of Dowel Power Same</td>
<td>post 64</td>
<td>59</td>
<td>113</td>
<td>89</td>
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<td>Shoulder abduction, degree</td>
<td>post 61</td>
<td>51</td>
<td>71</td>
<td>60</td>
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<td>Transport phase of water bottle</td>
<td>pre 42</td>
<td>−12</td>
<td>DA</td>
<td>Unable</td>
<td>48</td>
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<td>Forearm supination, degree</td>
<td>post DA</td>
<td>6</td>
<td>46</td>
<td>38</td>
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<td>Dowel Power Opposite (palm up)</td>
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<td>5.1</td>
<td>0.8</td>
<td>2.3</td>
<td>0.1</td>
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<td>Trunk forward translation, cm</td>
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<td>3.3</td>
<td>0.8</td>
<td>0.2</td>
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<td>Trunk medial translation, cm</td>
<td>pre 2.4</td>
<td>2.6</td>
<td>4.5</td>
<td>6.3</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>post 5.6</td>
<td>6.7</td>
<td>3.6</td>
<td>3.1</td>
<td></td>
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<tr>
<td>Humeral head forward translation, cm</td>
<td>pre 2.6</td>
<td>7.7</td>
<td>13.0</td>
<td>5.0</td>
<td>2.3</td>
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<td></td>
<td>post 14.9</td>
<td>6.1</td>
<td>12.8</td>
<td>6.7</td>
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<tr>
<td>Humeral head medial translation, cm</td>
<td>pre 2.5</td>
<td>5.9</td>
<td>3.7</td>
<td>1.5</td>
<td>2.0</td>
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<tr>
<td></td>
<td>post 6.2</td>
<td>6.6</td>
<td>4.9</td>
<td>2.5</td>
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<td>Humeral head vertical translation, cm</td>
<td>pre 10.9</td>
<td>9.0</td>
<td>15.0</td>
<td>18.0</td>
<td>6.8</td>
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<tr>
<td></td>
<td>post 13.0</td>
<td>1.4</td>
<td>14.8</td>
<td>19.6</td>
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<tr>
<td>Speed</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Peak reach hand velocity, cm/s</td>
<td>pre 66</td>
<td>32</td>
<td>13</td>
<td>43</td>
<td>70</td>
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<tr>
<td>Dowel Power Same</td>
<td>post 42</td>
<td>31</td>
<td>26</td>
<td>41</td>
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<td>Smoothness</td>
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<td>Distal: no. of zero crossings in aperture acceleration</td>
<td>pre 12</td>
<td>14</td>
<td>26</td>
<td>22</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>post 28</td>
<td>8</td>
<td>12</td>
<td>12</td>
<td></td>
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<tr>
<td>Reach phase of Dowel Power Same</td>
<td>pre 3</td>
<td>6</td>
<td>11</td>
<td>14</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>post 5</td>
<td>5</td>
<td>9</td>
<td>4</td>
<td></td>
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<td>Proximal: no. of zero crossings in hand acceleration</td>
<td>pre 10</td>
<td>20</td>
<td>29</td>
<td>19</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>post 17</td>
<td>21</td>
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<td>Interjoint coordination</td>
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<tr>
<td>Distal: aperture/elbow extension, r value</td>
<td>pre −0.91</td>
<td>−0.48</td>
<td>−0.93</td>
<td>−0.78</td>
<td>−0.96</td>
</tr>
<tr>
<td></td>
<td>post −0.99</td>
<td>−0.76</td>
<td>−0.88</td>
<td>−0.95</td>
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<tr>
<td>Reach phase of Dowel Power Same</td>
<td>pre +0.95</td>
<td>+0.17</td>
<td>+0.96</td>
<td>+0.54</td>
<td>−0.94</td>
</tr>
<tr>
<td></td>
<td>post −0.99</td>
<td>−0.88</td>
<td>+0.96</td>
<td>+0.86</td>
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Note: RLA = Rancho Los Amigos; WMFT = Wolf Motor Function Test; DA = did not attempt.
Reach time decreased for all three ASAP intervention subjects by an average of 0.98 seconds, moving closer to the normal value of 0.49 seconds, but remained markedly prolonged at 1.27 seconds. Reach time increased slightly in the UCC subject.

Figure 2 highlights the changes in the kinematics of the water bottle task after ASAP. Aperture increased for all ASAP subjects particularly when reaching for the water bottle, the largest diameter object, with the aperture for ASAP subjects 1 and 3 (14.5 and 13.7 cm) exceeding that of the able-bodied subject (12.8 cm). In contrast, aperture decreased slightly for the UCC subject (from 12.2 to 10.8 cm). The peak extension angles of both the wrist and elbow increased for the ASAP intervention subjects as well as the control subject. Wrist extension was greater than the normal value in ASAP subjects 1 and 2 (39° compared to 28° in the able-bodied subjects), indicating that increased wrist extension may be a substitution strategy to facilitate finger extension. In contrast, elbow extension, although improved in all stroke subjects, was still significantly less than that in the able-bodied subjects. Shoulder abduction was excessive during reach and during transport of the water bottle to the mouth in the stroke subjects (particularly in the two ASAP subjects with the greatest initial severity, i.e., lowest Fugl-Meyer scores) compared to the able-bodied subjects. This motion pattern indicates substitution of excessive shoulder abduction for inadequate elbow extension during reach and dominance of the flexion synergy (shoulder abduction with elbow flexion) during hand to mouth activities. The dominance of the flexion synergy is also seen in the proximal interjoint coordination values, which are high and

<table>
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<th>Muscle</th>
<th>Usual care control</th>
<th>ASAP-2 (RLA)</th>
<th>ASAP-3 (RLA)</th>
<th>Able-bodied mean of 3</th>
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<tr>
<td>EDC reach</td>
<td>pre 26</td>
<td>27</td>
<td>45</td>
<td>23</td>
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<tr>
<td>ECR grasp</td>
<td>pre 37</td>
<td>26</td>
<td>29</td>
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<td>post 14</td>
<td>44</td>
<td>58</td>
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<td>FCR transport</td>
<td>pre 21</td>
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<tr>
<td>EDC reach</td>
<td>post 7</td>
<td>30</td>
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<td>FCR transport</td>
<td>post 4</td>
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</table>

Note: ASAP = Accelerated Skill Acquisition Program; RLA = Rancho Los Amigos; EDC = extensor digitorum communis; ECR = extensor carpi radialis; FDP = flexor digitorum profundus; FCR = flexor carpi radialis.

Figure 2. Partial recovery of normal kinematics in the water bottle task. After ASAP training, the stroke subject completed the task with greater aperture, more elbow and wrist extension, and less shoulder abduction. After ASAP, the peak values in these degrees of freedom approached those used by the able-bodied subject.
negative for able-bodied subjects (mean = −0.94) but were mostly high and positive for the stroke subjects, indicating that shoulder abduction is accompanying elbow flexion in bringing the hand to the mouth rather than shoulder adduction as seen in able-bodied subjects. Smoothness of the hand path (representing proximal control) improved toward normal in two of the three ASAP subjects and decreased slightly in the UCC subject. Distal smoothness of the aperture improved in all three ASAP subjects, improving to near normal in the subject with highest initial function, and decreased significantly in the UCC subject. Excessive forward and medial trunk motion was reduced in the ASAP subjects while translation of the humeral head (shoulder girdle and scapular motion) remained markedly increased (Figure 3).

Subjects performed two different reach and transport tasks with the dowel. In the Dowel Power Same task, subjects were instructed to place the end of the dowel closer to the target in the target receptacle (Figure 1). All of the subjects accomplished this goal by reaching for the dowel with the hand over the object and the forearm in pronation. Placing the dowel in the target was accomplished with slight supination, shoulder abduction, and external rotation. In the Dowel Power Opposite task, subjects were instructed to place the end of the dowel further from the target in the receptacle. No specific instructions were given in how best to accomplish this task. Able-bodied subjects chose one of two strategies, either an underhand grasp with supination and placing the dowel in the target with pronation or an overhand grasp with pronation and using further increased pronation and shoulder internal rotation for transport. In stroke subjects, the UCC subject was able to perform an underhand grasp with supination in both the pre- and postintervention assessments. Subject ASAP-3 attempted an underhand grasp initially but was unable to supinate his forearm sufficiently to complete the task. At the postintervention test, he was able to supinate enough to complete an underhand grasp. Subject ASAP-2 utilized the overhand grasp in the initial test and the underhand grasp in the postintervention test. Based on these results, we believe that the ability to perform an underhand grasp indicates a higher level of motor control and recovery.

Because there were two distinct patterns of EMG activity in the reach phase, one of primarily finger extensor activity that coincided with increasing aperture and a second phase with cessation of finger extensor activity and a burst of finger flexor activity that coincided with the onset of aperture closing, the reach phase was further divided into reach and grasp subphases for analysis of the EMG activity (Figure 2, Table 2). Reach was defined as the time of the hand leaving the start switch to the time of the beginning of aperture closing. Grasp began at aperture closing and ended with the lifting of the dowel or water bottle from the switch. Finger extensors (EDC) were most active during the reach phase to increase the aperture in preparation for grasp. Wrist extensors (ECR) were most intensely active during the grasp phase to stabilize the wrist in an extended position while the finger flexors contracted to encircle the dowel or water bottle. ECR intensity of activation increased in the two ASAP subjects and was inconsistent in the UCC

![Figure 3](Reduction of compensatory trunk movement (in cm) after ASAP in a single subject.)
subject. The finger flexors (FDP) had primary activity during the grasp and transport phases while the wrist flexor (FCR) was dominant only during transport. FDP of the subjects with stroke tended to have higher relative intensity than in the able-bodied subjects while FCR had abnormally low activity in the stroke subjects.

Conclusions

Our pilot data provided evidence for improved function resulting from both compensation and recovery. Improvements in movement time and extent, smoothness, and interjoint coordination of reach and grasp activities were demonstrated in the subjects receiving the experimental ASAP intervention, and in most cases similar improvements were not seen in the UCC. The amount of compensatory use of forward trunk movement was reduced after ASAP but increased in the UCC subject. Distal recovery (aperture, supination) was larger in the ASAP subjects than the UCC subject. The two ASAP intervention subjects with the greatest severity of UE hemiparesis prior to the intervention demonstrated greater use of proximal compensatory strategies and reliance on synergies in the initial assessment session, and these compensations were less dominant in the postintervention recordings (abduction ROM, proximal smoothness). The ASAP-1, the intervention subject with high initial function in his UE, improved primarily in distal control measures: aperture, distal smoothness, and distal interjoint coordination. Thus, both the extent and type of improvement in reach and grasp following the ASAP intervention were dependent on the severity of the initial UE impairment.

The changes in average movement time for the tasks in the WMFT were consistent with changes in performance time for the laboratory reach and grasp tasks. Subject ASAP-3 had the lowest baseline FM score, was the slowest in both the WMFT and reach and grasp tasks initially, and made the largest improvements in the postintervention assessment. This subject also made the largest gains in the WMFT Functional Ability score, which was consistent with his worsening smoothness and increased use of shoulder abduction, trunk motion, and vertical translation of the humeral head (indicating scapular elevation to substitute for limited shoulder flexion) in the laboratory tasks. The UCC subject appeared to use these compensatory strategies to complete one WMFT task at the post test that he was unable to complete at the pre test. Overall, he had slowed movement time in both the median WMFT times and reach and grasp performance times. Our interpretation is that he learned compensatory techniques for improving function but that, on average, this would translate into less actual use in the real-world environment over time as the slow and awkward movements become frustrating for most individuals.

Data Reduction Methods

One of the daunting aspects to comprehensive kinematic and EMG studies is the generation of a large number of potentially correlated dependent variables. Although it is possible to choose a priori a small number of primary outcome variables based on previous studies, this is particularly challenging in complex upper limb tasks that entail a large number of DOFs and potentially important variables. For example, in the case studies presented, we examined 11 ROM variables (forward torso lean, lateral torso lean, torso twist, scapular movement, glenohumeral flexion, glenohumeral abduction, glenohumeral internal/external rotation, elbow flexion/extension, supination/pronation, wrist flexion/extension, and aperture), two smoothness variables (distal, proximal), and two interjoint coordination variables (distal, proximal). Five tasks were used, with each task having four phases (reach, grasp, transport, release). Therefore, when examining kinematics alone, a total of 300 (15 variables × 4 phases × 5 tasks) dependent variables would be available for each subject. Fortunately, several powerful methods of data reduction are available that can identify the constructs that underlie the data and allow assessment of the strength of latent variables (i.e., compensation vs. recovery) within a given treatment group. Investigators often reduce data by averaging across
outcome variables, but doing so blindly can lead to loss of important information or nonoptimal reduction of the data set into the most important factors that represent the data. The following techniques offer approaches to data reduction based on the structure of the data itself (principal components analysis) or based on confirmation of *a priori* assumptions on the underlying data structure (confirmatory factor analysis).

**Principal components analysis**

Principal components analysis (PCA), a technique for reducing complexity when there are multiple correlated observed measures, is used in a wide variety of applications in psychology, medicine, engineering, and genetics (15,591 references in PubMed as of April 2009). This method has been used to examine the dimensionality of the Fugl-Meyer assessment of upper extremity function to measure subtle changes in gait kinematics within subjects that were predictive of improved functioning in several studies of abnormal and normal gait, and to examine arm coordination. One recent review concluded that the potential of PCA “for the (clinical) study of human movement sciences (e.g., diagnostics and evaluation of interventions) is evident but still largely untapped.”

In the rehabilitation literature, PCA has primarily been used on within-subjects data to determine how many dimensions are necessary to capture most of the across-time covariance in muscle activation patterns or kinematics. PCA can also be used across subjects with both kinematic and EMG data, using mean EMG and movement scores averaged across trials for each task-phase combination as the input data. For example, each subject receives a score for mean aperture during reach in the bottle task and in every other Task × Phase combination. A typical study might include 8 EMG scores and 11 ROM variables, so there are 19 movement scores in each of 20 Task × Phase combinations for each subject. PCA can be done on each of these 20 combinations in order to determine whether the loading matrices from different Task × Phase combinations are similar. If loading matrices for several Task × Phase combinations are not significantly different (i.e., similar items load on factors and the item weights are similar), then we can combine these Task × Phase combinations by averaging across them for each variable for each subject. Multilevel factoring can be used to determine whether factor structures differ significantly across tasks within a given phase. For example, if we find that the kinematic variables have similar factor loadings in the reach phase across the five tasks, we can average each kinematic variable across these tasks and redo the PCA on these average scores, producing a single factor loading matrix for the reach phase across all tasks. This may reduce the number of distinct Task × Phase combinations from 20 down to 4, for example, if the factor patterns within each phase tend to be the same across the five tasks. If this were the case, and if PCA found an average of two factors were necessary to explain most of the variance within each phase, then we would have reduced the complexity of the data set down from 380 variables per subject (19 scores on each of 20 Task × Phase combinations) to 8 scores (2 factor scores on each of 4 phases), which represent most of the information contained in the original 380 variables. Our preliminary examination of factor loadings for 19 kinematic and EMG variables, across time within tasks and within subjects, found that in every case no more than five factors were necessary to account for the majority of variance when looking at all four movement phases combined. Therefore we expect that no more than two factors should be necessary to account for most of the variance within any one phase.

PCA tells us how many variables we need in order to capture most of the variance in the original kinematic and EMG measures. Once this is determined, factor scores computed for each subject can then be compared across treatment conditions and can be used as predictors of clinical outcomes. Each factor score indicates the strength of a particular group of EMG or kinematic variables during a particular movement phase. For example, we might find that during the reach phase, subjects tend to (a) extend the elbow, (b) flex the shoulder, and (c) increase aperture. If this were true, these variables would load together on a factor for the reach phase, and other variables would have little or no loading on this factor. A subject’s score on this factor would indicate the strength of these particular movements during this phase. A comparison between treatment groups on this factor would tell us whether subjects in
different treatment conditions use this pattern to a similar degree during this phase.

Confirmatory factor analysis and structural equation modeling

Confirmatory factor analysis (CFA) is a type of structural equation model (SEM) that tests a measurement model that is specified a priori. CFA has been used to test measurement models for gait and arm function following stroke using the Motor Assessment Scale. SEM is a powerful and flexible method for testing both causal and measurement models using complex data sets. The strategy is to evaluate the fit of a specified model to the observed data. For example, Figure 4 shows a possible EMG measurement model for agonist-activation. If this model fits, it allows for significant data reduction but also tests the hypothesis that agonist-activation across DOFs, phases, and tasks form a

![Diagram of agonist activation](attachment:image.png)

**Figure 4.** A possible measurement model for agonist activation. In this model, the observed data are EMG scores (%MVC) for various muscles defined as agonists for the particular phase (from examination of data from normal controls). There are four movement phases (reach, grasp, transport, release) measured in two trials for each of four tasks (bottle, cheerio, dowel, domino). For simplicity, the four tasks and eight trials are only shown for one muscle in this figure (biceps during transport phase) but would actually be used with each Muscle x Phase combination. The score for the bottle task here would be the mean biceps EMG across two trials, during the transport phase of the bottle task. The score for biceps would be the mean of bottle, cheerio, dowel, and domino. The score for the transport phase within elbow would be the mean of biceps and brachioradialis. Elbow is measured by reach and transport movement phases. Agonist activation is a higher order construct made up of scores on finger, wrist, and elbow. Path coefficients show the strength of each lower order construct as an indicator of the higher order construct (i.e., its measurement reliability). If this model fit the data, it would allow for 88 single-trial EMG scores to be summarized by a single higher order construct score. As the path coefficients from agonist-activation to finger, wrist, and elbow become larger, the score for the higher order construct becomes more reliable. FDP = flexor digitorum profundus; FDS = flexor digitorum superficialis; EDC = extensor digitorum communis; FCR = flexor carpi radialis; FCU = flexor carpi ulnaris; ECR = extensor carpi radialis; ECU = extensor carpi ulnaris.
This unidimensional higher order construct. This type of measurement model can then be included in a causal model. For example in Figure 5, agonist-activation, as defined in Figure 4, is used as one mediator of the treatment effect. Here, treatment is a binary predictor variable (ASAP vs. other treatment), three latent variables measuring factors (agonist-activation, movement fluidity, and ROM) are specified as mediators, and the outcome is increased arm use at home. A model like this could be used to test whether these three factors “explain” the treatment effect of ASAP on use at home, as well as the relative importance of these three latent variables.

In addition to mediator effects like these, we can also test moderator effects using the multilevel modeling features in Mplus. For example, we could test whether the regression model of increased arm use at home on the three latent predictors in Figure 5 is the same across treatment groups. This strategy can also be used to develop measurement models for Recovery and Compensation and then test their mediator and moderator effects on clinical outcomes. Without data, it is not possible
to say precisely how these concepts will be defined, but one can imagine a Recovery latent variable that is measured by increased distal interjoint coordination, increased proximal (shoulder-elbow) interjoint coordination, increased distal ROM, increased agonist-activation, and reduced antagonist coactivation and a Compensation latent variable that is measured by increased proximal ROM and decreased agonist-activation. If we can develop well-fitting measurement models of these constructs, we can then test models examining how these latent variables mediate the treatment effect on outcomes such as impairment and activity limitation assessments as well as assessments of real-world arm use such as MAL. Using multilevel SEM, we can also examine whether the treatment groups differ in the roles that Recovery and Compensation play as mediators and moderators of the treatment effect. For example, we might find that after ASAP treatment, Recovery predicts both WFMT and arm use at home, whereas in other treatment groups, Compensation predicts WFMT but not arm use at home. This kind of information can help us to identify specific movement variables that lead to important clinical outcomes, which will allow us to improve treatment effectiveness.

We acknowledge that variables other than kinematics and EMG can impact amount of arm use. For example, the full range of personality and diagnostic variables that could potentially help to explain treatment responses can easily be included in SEM. A model testing the mediating effect of recovery could also include a latent variable for depression and a latent variable for motivation. These variables might have direct negative effects on amount of arm use and also might moderate the effect of treatment on recovery. However, we also acknowledge that successful application of these methods requires a large number of subjects when testing very complex models that include hierarchical measurement models embedded within causal models.

Conclusions

We propose the following hypotheses to explain the poor outcome in the upper limb after stroke: (a) functional gains in the UE can occur via recovery or compensation; (b) traditional treatment approaches encourage adoption of compensatory strategies early in the postacute period that can prevent potential recovery; and (c) increased arm use at home is strongly predicted by increased recovery and only weakly predicted by increased function via compensation. Our pilot data demonstrated clear recovery in the subjects who received the ASAP intervention where impairment reduction is the primary goal, whereas a UCC subject showed increased use of compensatory adaptations over the same period. These different patterns of functional gain were identified by use of comprehensive kinematic and EMG analysis, which may lead to important insights regarding use of the arm in the home environment. Data analysis methods such as PCA, CFA, and SEM identify the constructs that underlie the large kinematic and EMG data sets generated by performance of complex ADL tasks. These constructs will provide detailed information on the location, extent, and type of change affected by experimental interventions. This in turn would provide a scientific rationale for development of new interventions.

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