Practice Effects on the Less-Affected Upper Extremity After Stroke

Patricia S. Pohl, PhD, Carolee J. Winstein, PhD


Objective: To test the hypotheses that (1) adults who have had a stroke, using the less affected upper extremity (UE), improve performance of an aiming task with practice, and (2) compared with control subjects, stroke patients show less improvement in a complex condition.

Design: Movement time (MT) and kinematic data were collected over practice. Comparisons were made between the less-affected UE of stroke patients and the same hand of controls.

Setting: A human performance laboratory.

Participants: A matched sample of right-handed adults, 10 with unilateral stroke and 10 nondisabled controls.

Intervention: Practice of an aiming task in an easy and complex condition as defined by target width and distance between two targets.

Main Outcome Measures: MT, peak velocity, and temporal phases of the trajectory.

Results: Adults who had experienced a stroke had persistently longer MTs than control subjects; however, all participants achieved faster MTs with practice in both conditions. The absolute amount of time in each temporal phase decreased without a change in the relative times. Peak velocity increased only in the easy condition.

Conclusions: Adults with stroke damage can improve motor performance of the less-affected UE with practice. Further study is needed to see if practice effects are permanent and generalizable.

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Individuals who suffer unilateral stroke are often left with bilateral upper extremity (UE) involvement. Although the UE contralateral to the side of the cerebral lesion is clearly more affected, the UE ipsilateral to the lesion is not normal. Movements of the less-affected UE in adults with unilateral stroke are weaker and less accurate than the UEs of healthy control adults. In goal-directed aiming movements that require both speed and accuracy, adults who have experienced stroke demonstrate slower movements when using the less-affected UE than do adults without brain damage.

Motor deficits in the less-affected UE may be partially explained by the fact that there is bilateral cortical hemisphere activity during unilateral UE movements in adults without brain damage. Winstein and colleagues performed a study using positron emission tomography (PET) on young adults as they performed a rapid, accurate aiming task with their dominant right hand in three conditions of task complexity. Task complexity was defined by the width of the targets and the distance between the targets. Of particular interest, there was an increase in activity in right dorsal premotor, bilateral supplementary motor areas (SMAs), and bilateral occipital areas with performance in the high-complexity condition. This finding matches those of other studies that have shown that the planning and execution of unimanual goal-directed tasks are accompanied by bilateral cortical activation. Thus, damage in one hemisphere may affect the motor control of both UEs.

Practice is the most powerful variable in the acquisition of motor skill. Practice of arm movements with dual goals of speed and accuracy result in faster movement times (MTs) without a loss of accuracy for both young adults and older adults. Participants in the aforementioned studies have been nondisabled adults. Can motor control of the less-affected UE of adults who have had a stroke be improved with practice? Most studies that have examined performance of the less-affected UE have restricted measurements to relatively few trials. It is not clear if these motor control deficits are fixed, or if they can be ameliorated with practice. Thus, the first purpose of this study was to determine whether practice affects performance of the less-affected UE in adult stroke patients. If motor control of that extremity can be improved with practice, adults who have experienced stroke should be able to decrease MT with practice of an aiming task, as with nondisabled adults.

A study of practice effects on the performance of aiming in nondisabled adults found that the kinematic parameters following practice are a function of the complexity of the task. In a low-complexity condition, a decrease in MT is achieved by speeding (ie, increasing peak velocity) without changing the relative temporal structure (ie, the shape of the velocity profile). Equal amounts of MT are spent in acceleration and deceleration, and this does not change with practice. In a high-complexity condition, movement times are decreased by changing the relative temporal structure (ie, increase symmetry in the velocity profile with an increase in the relative time spent in acceleration) without changing the scaling (ie, peak velocity). Both young and older adults demonstrate these patterns of change with practice, suggesting that these strategies are related more to the complexity of the task than to age.

If bilateral cortical activation is associated with performance in high-complexity conditions, it is reasonable to suggest that persons with unilateral cortical damage may have difficulty improving performance in conditions of high task complexity. Therefore, the second purpose of this study was to examine practice effects on MT as a function of task complexity. If activation of both cortices is necessary for rigid and accurate
aiming in a high-complexity condition, adults who have experienced stroke may not be able to decrease MT with practice in a more complex task condition or they may do so using different strategies than controls.

METHODS

Participants
Twenty self-declared right-hand–dominant adults participated in the study, including 10 with unilateral cerebral lesions and 10 gender- and age-matched neurologically healthy control subjects (table 1). All participants with stroke were at least 6 months from onset (43 ± 30mo, range 6 to 84mo), thus it was assumed that the period of the greatest and most rapid natural recovery was past. The stroke survivors were no longer undergoing physical rehabilitation and none were participating in formal exercise programs. Unilateral brain damage was determined from brain imaging reports and medical records, or, in three cases where these were not available, by patient history. The cause of the stroke was not recorded. Using the clinical classification system described by Bamford and colleagues,17 we were able to determine that none of the participants with stroke damage had lesions involving the posterior circulation. The stroke patients were screened for hemineglect syndrome (table 1) with the Schenkenberg line bisection test.18 Before beginning the practice phase of the study, a clinical assessment of right and left UE function for each stroke patient was done using the motor UE section of the Fugl-Meyer Assessment.19 Comparisons using the Mann-Whitney test indicated that time since onset, line bisection scores, and Fugl-Meyer scores were not different between those with right hemisphere lesion and those with left hemisphere lesion.

Instrumentation and Task
The instrumentation6 and task7,8,16 have been described elsewhere. Equipment for the aiming task included a hand-held stylus, a millisecond timer for trial length that emitted an audible tone at the end of the trial, and a tapping board with metal plates distinguishing two target regions and surrounding “error” areas with impulse counters for target hits, overshoots, and undershoots at each target. Task complexity was based on Fitts’ Law6 where MT increases as the Index of Difficulty (ID) increases. The ID is calculated in bits and is equal to the Log2 (2D/W) where D is the distance between the targets and W is the width of the targets. The low-complexity condition was defined by two 8cm-wide targets placed 37cm apart (ID = 3.21 bits). The high-complexity condition was defined by two 0.5cm-wide targets placed 18.5cm apart (ID = 6.21 bits).

Participants were seated at a table midline to the tapping board, such that aiming movements were made in the frontal plane. They were required to hold the stylus like a pencil, resting the tip of the stylus on the target to their left. Individuals who had experienced stroke performed the task with the less-affected UE. Controls performed with the same UE as the stroke patients to whom they were matched.

The task required the participants to tap in a reciprocal fashion with the stylus, hitting each target alternately for 10sec as quickly and as accurately as possible. The start of the trial (defined by the first target hit on the plate to the performer’s right), and each subsequent target hit, was signaled by light-emitting diodes (LED) in view of the camera but not the performer. Video recording was done with a Pulnix 120/60Hz video camera. Video analysis equipment included Peak Performance Technologies® software and hardware interfaced with the video recorder.

Procedure
Participants signed an informed consent approved by the university’s Institutional Review Board. Participants were seated with the chair adjusted so that, with the arm next to the trunk and the shoulder relaxed, the forearm was approximately parallel to the tabletop with the elbow flexed.

Participants were instructed to begin the trial any time after the experimenter indicated she was ready (reaction time was not measured) and to continue the tapping movements until they heard the tone which terminates the trial after 10sec. They were instructed to move as quickly as possible without missing the targets. No practice trials were permitted before data collection began.

Participants performed the aiming movement under conditions of low and high task complexity in 10 trial practice blocks of each condition. There was approximately a 15sec rest between trials, and a 2min rest between blocks when the condition changed. In addition, participants were encouraged to rest between trials if a rest was needed. Participants performed sequences of one practice block of the low-complexity condition and two practice blocks of the high-complexity condition until they had reached 500 target hits in any one condition, at which time they continued until they reached 500 target hits in the other condition. This practice block order was established from pilot data that indicated that at least twice the number of trials was needed in the high-complexity condition versus the low-complexity condition to achieve 500 target hits.

Within any trial, the number of target misses could not be greater than 10% of the total number of passes from target to target. If this error criterion was not met, the trial was calculated in bits and is equal to the Log2 (2D/W) where D is the distance between the targets and W is the width of the targets. The low-complexity condition was defined by two 8cm-wide targets placed 37cm apart (ID = 3.21 bits). The high-complexity condition was defined by two 0.5cm-wide targets placed 18.5cm apart (ID = 6.21 bits).

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Within any trial, the number of target misses could not be greater than 10% of the total number of passes from target to target. If this error criterion was not met, the trial was...
unacceptable and the target hits in that trial were not counted toward the 500 required hits. Feedback was provided after each trial; participants were told the number of target hits they obtained, if the trial was acceptable, and the total number of target hits accumulated in that condition.

Stylus movements were videotaped at a rate of 120Hz during all trials, using a split screen. The camera was placed orthogonal to the major plane of interest. A reflective marker, fixed 1 cm from the distal end of the stylus, was used during the video digitizing process to determine the trajectory of the movements. Room lights remained on for all filming. Total testing time, including screening tests, was between 2 and 3 hours.

Data Analysis

Digitized movement of the stylus provided horizontal (x) and vertical (y) coordinates of the trajectories sampled every 8.33 msec. Position data were smoothed using a Butterworth low-pass digital filter with an 8 Hz cutoff frequency supplied by the Peak Performance Motion Analysis System. Velocities were derived from the position data using a five-point central difference algorithm.

Movement time and key kinematic features were identified using DATA-PAC II software from RUN Technologies. Target hits were defined by the lowest horizontal and vertical positions (fig 1). Movement time was the absolute time taken from lift-off from one target to lift-off at the other target (ie, a cycle). Movement time was divided into three temporal phases: (1) acceleration time (ie, time from lift-off from a target to peak horizontal velocity), (2) deceleration time (ie, time from peak horizontal velocity to target hit), and (3) dwell time (ie, the length of time the stylus rested on a target, defined by the duration of zero vertical velocity). In addition to the absolute duration of each of these temporal phases, the proportion of MT spent in each phase was calculated as a measure of relative time. Peak horizontal velocity was the maximum velocity attained in the major plane of movement.

Dependent measures were extracted from each cycle of interest. Averages for each measure were computed across cycles in blocks of 10 for a total of 14 practice blocks (table 2).

The number of unacceptable trials was counted for each participant in each condition and analyzed in a two-factor, 2 group (stroke, control) X 2 complexity (low, high) analysis of variance (ANOVA). No single model was appropriate for all dependent measures. Thus, we conducted separate three-factor, 2 group (stroke, control) X 2 complexity (low, high) X practice

<table>
<thead>
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<th>Table 2: Composition of Practice Blocks for Analyses</th>
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<tr>
<td>Practice Block</td>
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blocks (1-14) ANOVAs with repeated measures on the last factor for each other dependent measure. The Greenhouse-Geisser adjusted degrees of freedom was used for the repeated measures factor of practice blocks. The level of significance was set at $p < .05$ for all analyses. Effect sizes were calculated in the form of eta squared ($\eta^2$) using the SPSS statistical package.

To gain insight into the effects of the side of the lesion, descriptive analyses were done on performance over practice for right-stroke and left-stroke patients. To avoid differences owing to the hand used for the task, the data from the stroke subjects were compared with that from control subjects using the same hand.

**RESULTS**

**Task Complexity**
Performance markedly differed as a function of task complexity, with average MTs of 347msec and 900msec in the low- and high-complexity conditions, respectively. To accumulate the required 500 target hits in each condition, participants needed an average of 17 acceptable trials (approximately 30 hits per trial) in the low-complexity condition and 42 acceptable trials (approximately 12 hits per trial) in the high-complexity condition.

Statistical analyses revealed that the effect of task complexity was robust, with a significant main effect of complexity for MT and each kinematic measure at $p < .0001$, with the exception of relative dwell time, which resulted in a main effect of complexity of $p < .02$. Participants had more unacceptable trials in the high-complexity condition. Indeed, the main effect of task complexity for the frequency of unacceptable trials was significant at $p < .04$. The results reported here concern the effects of group, practice block, and interactions with complexity. When main effects and interactions are present, only the higher order interaction is presented.

**Unacceptable Trials**
Each group, adults who have had stroke and control subjects, had five unacceptable trials in the low-complexity condition. In the high-complexity condition, the stroke subjects had a total of 69 unacceptable trials compared with a total of 35 for control subjects; however, this difference was not significant.

**Temporal Measures**
Across practice blocks, stroke patients had longer MTs compared with control subjects in each complexity condition (table 3). This was reliable as evidenced by a main effect of group, $p < .02$, $\eta^2 = .22$.

Stroke and control participants decreased MT with practice in both conditions of task complexity (fig 2). The decrease in MT was reliable as indicated by a main effect of practice block, $p < .0001$, $\eta^2 = .34$.

The stroke-affected adults tended to spend more absolute time in each temporal phase compared with the control subjects (table 3); however, these differences were not significant. There were no group differences found in relative time of the three temporal phases (table 3). With practice, all participants decreased the absolute time spent in each temporal phase (fig 2). There were main effects of practice block for acceleration ($p < .0001$, $\eta^2 = .26$); deceleration ($p < .0001$, $\eta^2 = .18$); and dwell time ($p < .05$, $\eta^2 = .32$). The relative time spent in each temporal phase did not change with practice.

**Peak Horizontal Velocity**
Across practice blocks, stroke-affected adults had lower peak horizontal velocities compared with control subjects in the low-, but not the high-, complexity condition (table 3). This resulted in a complexity by group interaction, $p < .007$, $\eta^2 = .14$.

Both groups increased peak horizontal velocity with practice in the low-complexity condition from an average of 149cm/sec in the first practice block to 208cm/sec in the last practice block. In contrast, there was little change in peak velocity with practice in the High-complexity condition; the average peak velocity was 69cm/sec in the first block and 70cm/sec in the last block. The complexity $\times$ practice block interaction was significant, $p < .0001$, $\eta^2 = .29$.

**Right Versus Left Stroke**
Although not a primary question of this study and with too small a sample size to permit statistical analyses, some interesting trends emerged in the performance of individuals affected by stroke on the right versus left compared with control subjects using the same hand. For participants using the right hand, approximately 36% of MT was spent in acceleration, 53% in deceleration, and 11% in dwell time, and these percentages did not change significantly with practice. Controls using the left hand had a similar temporal distribution over practice to those

<table>
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<th>Movement time (msec)*</th>
<th>Low Complexity</th>
<th>High Complexity</th>
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<tbody>
<tr>
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<td>Control</td>
<td>Stroke</td>
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<tr>
<td>393 (9)</td>
<td>302 (5)</td>
<td>953 (14)</td>
</tr>
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<table>
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<tr>
<th>Absolute time (msec)</th>
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<th>High Complexity</th>
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<tbody>
<tr>
<td>Stroke</td>
<td>Control</td>
<td>Stroke</td>
</tr>
<tr>
<td>197 (5)</td>
<td>157 (3)</td>
<td>266 (6)</td>
</tr>
<tr>
<td>Deceleration</td>
<td>145 (4)</td>
<td>108 (5)</td>
</tr>
<tr>
<td>Dwell</td>
<td>50 (2)</td>
<td>36 (1)</td>
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<table>
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<tr>
<th>Relative time (%)</th>
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<td>Control</td>
<td>Stroke</td>
</tr>
<tr>
<td>Acceleration</td>
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<td>52 (0)</td>
</tr>
<tr>
<td>Deceleration</td>
<td>37 (0)</td>
<td>36 (0)</td>
</tr>
<tr>
<td>Dwell</td>
<td>13 (0)</td>
<td>12 (0)</td>
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Table 3: Mean and Standard Error of the Mean for Movement Times and Kinematic Measures Across Practice

* Group, $p < .02$.  † Complexity $\times$ group, $p < .007$.

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These prolonged dwell times, with an absolute duration of approximately 300msec and over twice that of all other participants, were demonstrated by all five participants with left stroke lesion and persisted over practice.

Figure 4 gives an example of the prolonged dwell times of one participant with left stroke lesion (left side series) compared with a control subject using the left hand (right side series). The time series of the participant with left stroke lesion show prolonged zero positions and velocities in the horizontal and vertical dimensions at the same point in time (eg, just prior to 2sec). As indicated in plot D, these times without movement are dwell times, ie, the times the stylus rested on a target. In contrast, the time series of the control show brief zero positions and velocities at target hit, as indicated in plot H. Dwell times for this participant were brief.

**DISCUSSION**

The present study demonstrates that, with practice, stroke-affected adults can achieve faster movements with the less-affected UE, but the movements remain slower than in unafflicted control subjects. Previous work has demonstrated a slowing in the less-affected UE in adults with unilateral brain damage in tasks such as aiming between two targets, single target tapping, and sequencing hand postures. Extending these findings, results of the present study suggest that practice can ameliorate some of these motor performance deficits.

Practice is the foundation of the physical rehabilitation of adults who have suffered stroke. There is some, albeit surprisingly little, evidence that motor performance can be improved with practice in these persons. Motor control of the paretic, contralateral UE after stroke can be improved in some individuals through rigorous practice or forced use in which the less-affected UE is physically restrained. Other less-rigorous practice schedules have resulted in improved performance of the paretic UE.

Although motor deficits in the less-affected UE have been documented, investigators have not studied the effects of practice on these deficits. Some studies have measured motor recovery of the less-affected UE without including any specific intervention. Marque and colleagues evaluated motor function of the less-affected, left UE 20 and 90 days after onset of left stroke. Tests included hand dynamometry, elbow and wrist isokinetic testing, finger tapping, and a pegboard task. At 20 days, ipsilateral deficits were found in all but finger tapping in comparison with control subjects. At 90 days, the only ipsilateral UE motor function that remained impaired was performance in the pegboard task. Jones and colleagues reported reduced grip strength and proximal strength of the less-affected UE is physically restrained. Other less-rigorous practice schedules have resulted in improved performance of the paretic UE.

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using the right hand, differing only by 1% in acceleration and deceleration and having the same relative dwell time. In contrast, individuals with left stroke lesion spent 26% of MT in acceleration, 42% in deceleration, and 32% in dwell time. These prolonged dwell times, with an absolute duration of approximately 300msec and over twice that of all other
Lesion, particularly in those with left lesions.\textsuperscript{7,2,0,31,32} The present study included too few subjects to address issues of laterality, however the trend toward longer dwell times in the high-complexity condition for those with stroke (fig 4) may be related to the inclusion of subjects with left hemisphere lesions.

Motor deficits of the ipsilateral UE after stroke may also reflect disruption in bilateral hemispheric activation. Studies that have used brain imaging have documented bilateral hemispheric activation with unimanual goal-directed actions.\textsuperscript{8,10,11} Of note, ipsilateral and bilateral hemispheric activation are more prevalent in high-task-complexity conditions.\textsuperscript{8} This association led to our hypothesis that participants who had suffered stroke, compared with control participants, would not show improvement with practice in the high-complexity condition. This hypothesis was not supported by the results of this study. The stroke subjects, like the control participants, were able to decrease MT with practice in high- and low-complexity conditions, which was shown by the lack of a three-way interaction.

Fig 4. Time series of (A, E) horizontal position, (B, F) horizontal velocity, (C, G) vertical position, and (D, H) vertical velocity in the high-complexity condition. The left-side series is from an individual who had a left stroke; the right side from a control subject using the left hand.
group × complexity × practice block. This, however, may have been owing to the small number of participants, resulting in a small/medium effect size ($\eta^2 = .04$) and an observed power of .44. Further work with a greater number of participants could elucidate whether or not this finding is robust.

It is reasonable to suggest that the neural substrate responsible for the decrease in MT with practice is different for stroke versus control subjects. There is converging evidence from a variety of methodologies to suggest that motor recovery of the paretic UE is the result, at least in part, of an increase in activity in the nondamaged hemisphere. Clinical improvement in the paretic UE was associated with reorganization of the contralateral motor cortex and, to a lesser extent, the ipsilateral motor cortex. Undamaged contralateral nuclei may also contribute to motor recovery. Future studies of adults with stroke damage performing with the less-affected UE that use brain imaging or magnetic transcranial stimulation during motor skill acquisition may provide some insight into the interactions of pathology, practice, and skill acquisition.

In the present study, changes with practice in the kinematics of aiming were a function of the complexity of the task and were not different between stroke-afflicted individuals and control subjects. However, the observed power in this study to assess the block × group interaction was less than .50, so this result must be interpreted with caution. In the low-complexity condition, participants increased peak velocity with practice. The decrease in MT in the low-complexity condition was accompanied by a decrease in the absolute time spent in each temporal phase, while preserving relative time. These findings replicate the changes found in healthy young and older adults practicing aiming in a low-complexity condition when each participant was required to use the left, nondominant UE.

In the high-complexity condition, participants did not change peak velocity with practice. They did, however, decrease the absolute time spent in each temporal phase in the high-complexity condition without altering the relative temporal structure. This is in contrast to previous results in which healthy young and older adults, practicing in a high-complexity condition, altered the relative temporal structure by increasing relative acceleration time and decreasing relative dwell time. Older adults, performing in the same high-complexity condition as in the present study, spent an average of 31% of MT in acceleration time over practice, 52% in deceleration, and 17% in dwell time. These results are similar for the participants in the present study (four of the twenty participants were the same), except for those with left stroke damage who, using their left, nondominant UE, demonstrated prolonged absolute and relative dwell times (Fig. 4). The prolonged dwell times of those with left stroke damage are consistent with the prolonged reversals seen in those with left-sided brain damage. This protracted time in which the stylus is resting on the target is thought to reflect an inability to switch or sequence components of the movement. This finding is compatible with a specialized role for the left hemisphere in timing and sequencing movements or parts of movements. The absence of change with practice in relative dwell time in this small group of individuals with left stroke damage suggests that this aspect of motor control may be resistant to practice in those with left-sided brain damage. A larger group of participants is necessary for sufficient power to evaluate this statistically.

Physical rehabilitation of stroke patients should include rehabilitation of the less-affected UE. Even in individuals who are unable to regain use of the contralateral UE after stroke, functional improvements in UE tasks have been documented. It is likely that improved control of the less-affected UE was responsible at least in part for these functional gains.

The results of the present study demonstrate the effectiveness of practice in improving movement speed in the less-affected UE after stroke. Limitations in the study must be acknowledged. First, generalizations to the general stroke population must be made with caution. Screening narrowed subject selection to those who had suffered unilateral hemispheric stroke, and there were only 10 stroke subjects in our sample. The exclusion of those with receptive aphasia may have resulted in a sample population of those with left stroke damage with smaller lesions. Indeed the Fugl-Meyer motor scores of the contralateral UE of left stroke subjects tended to be higher than those of right stroke subjects (table 1), suggesting that they were less involved. Future studies with larger sample sizes and more detailed descriptions of the locations and extent of stroke are needed. Second, practice was limited to a single 1-day session. It is not known if additional practice or some specific intervention could lead to further improvement in motor control in the less-affected UE. Future studies are needed to evaluate the permanency of practice effects for the less-affected UE and to assess the transfer of improvements in motor control incurred during laboratory practice to everyday functional tasks.

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References


Suppliers

a. Pulnix America Inc., 770 Lucerne Drive, Sunnyvale, CA 94086.
b. Peak Performance Technologies, 7388 South Revere Parkway, Englewood, CO 80112.
c. RUN Technologies, 25622 Rolling Hills Roads, Laguna Hills, CA 92653.