**Return to Run after Stroke: A Case Series**

**Introduction**

Stroke often leads to sensorimotor impairments that make mobility tasks, like walking, more difficult.1,2 Despite sometimes extensive deficits in walking, stroke survivors have demonstrated the ability to improve walking speed and endurance.1,3-4 The high variability in mobility recovery from stroke suggests that some people will have low functional status (i.e., non-ambulatory) whereas others will wish to resume higher level tasks like running, after first recovering the ability to walk. Running is a component of many work, sport, and leisure activities within the community.5 The ability to run allows participation in such events, offers a return to pre-morbid functional levels for some, and may enhance quality of life post-stroke. Participation in the community is essential to well-being5 and clinicians must be prepared to meet the goals of their patients. Unfortunately, there is little research guiding clinicians on return to run after stroke.

To date, most of the literature is focused on the restoration of safe, efficient, and rapid independent walking.3 Despite some similarities, running is more difficult than walking due to the requirements for greater joint range of motion, strength, balance, and neuromuscular control.5-7 Running is distinguished from walking by the incorporation of a double float phase, in which both feet are off the ground at the same time.6-7 Increased running speed is first achieved by increasing stride length and then by increasing cadence.6 To achieve increased stride lengths and a double float period, greater limb propulsion is needed. Thus, ground reaction forces must be greater at toe off as the plantarflexors work to propel the body forward.7-8 Similarly, ground reaction forces during running are greater than walking during the weight acceptance (i.e., load absorption) phase, which is accomplished through greater knee joint flexion excursion and lengthening of the quadriceps muscle-tendon unit.6-7 For those who are rearfoot strikers, the ankle dorsiflexors are critical for absorbing load through the ankle6 but are often weak after stroke.

Given the increased task difficulty of running compared to walking and the associated sensorimotor deficits after stroke, challenges in running after stroke should not be surprising. Hemiparesis is common after stroke9 making both power generation and load absorption difficult. Increased muscle tone and spasticity may limit the available range of motion and the level of motor control necessary to progress through the running cycle. Balance is necessary to remain upright during walking, but postural control and balance deficits are common impairments after stroke.10-11 During running, dynamic stability is challenged by the absence of a double support period. Additionally, the typical forward trunk lean during running gait displaces the center of mass outside the base of support, requiring greater postural control to maintain equilibrium.

Despite the copious clinical and research efforts to maximize walking recovery post-stroke, there is little guidance for restoring running after stroke. We are aware of a single case report that showed intensive, task specific training improved running speed and ability after stroke in a 38-year old male.12 The next closest guidance comes from Williams and colleagues, 13 who worked with people with traumatic brain injury (TBI) to restore running function. Running may be a common goal for the relatively younger population of people who experience a TBI.13 There is growing evidence, however, that stroke is affecting younger and more active populations than once thought.14 Williams and Schache first developed a hierarchal framework for retraining high level mobility after TBI by using the HiMAT to quantify high level mobility, identify impairments and determine the next sequential mobility goal.13 This, coupled with comparison of biomechanical data specific to running in able bodied individuals is used to identify deficits and guide intervention strategy.13 Williams and Morris showed significant gains in high level mobility as measured by the HiMAT in TBI using this program.15 We hypothesize that Williams’ conceptual framework for retraining high level mobility in TBI is applicable to stroke populations.

Given some of the similarities between walking and running, similar general intervention strategies may be effective at improving running speed and quality. A focus on the biomechanics necessary for running, mixed with motor learning and exercise physiology principles, can be put into practice in a similar manner to gait training. Moderate to high intensity walking training improves both walking speed and distance in chronic stroke.4 Short interval high intensity treadmill training at fastest safe treadmill speed for 30 seconds bursts followed by 30-60 seconds of passive recovery is more successful than moderate intensity aerobic training at increasing gait speed in chronic stroke.16-18 Furthermore, a combination of treadmill and overground HIIT translates into overground gait speed increases.17 Lower extremity resistance training may be an important component towards improving gait speed in people with chronic stroke with the greatest effect size seen in programs lasting 12 weeks.1 Morgan et al showed that 8 weeks of power training improved walking speed, suggesting that high velocity concentric resistance training may help with forward propulsion during gait.19 We therefore hypothesize that a multidimensional approach including a high intensity running program modeled from established walking programs and running specific interventions targeting strength and power impairments will improve running ability.

The purpose of this study was to investigate the effectiveness of the combination of ankle power generation training, load absorption training and short interval HIIT to improve running ability in 3 participants with chronic stroke. We hypothesized that the 3 participants would improve their running ability as measured by running velocity, power generation, load absorption and performance in high level mobility tasks (HiMAT) following completion of a 12-week program.

**Case Descriptions**

Participant 1

History and Systems Review

The first participant (P1) was a 53-year-old male diagnosed with right hemiparesis from a stroke due to an occlusion of his L middle cerebral artery 20 months before the evaluation. His past medical history was unremarkable aside from complications from his stroke, including expressive aphasia and color agnosia. After the stroke, he had a three week stay in inpatient rehabilitation where he worked on gait, transfers, stair negotiation, bed mobility and completion of activities of daily living (ADLs). He was then discharged home with his supportive wife where he continued approximately 6 months of outpatient physical therapy. At our initial evaluation, he reported no falls in the previous 6 months. He had started running independently approximately 12 months after the stroke and typically completed 2-mile distances about twice per week. He stated that these running sessions sometimes included intermittent walking. Before his stroke, he was physically active, running approximately 3 times per week and participating in recreational races of 5 km and 10 km distances. He was a member of both his high school and collegiate track teams, competing in 5 km distances having achieved a personal record of 15:16 in the 5 km distance in college. During the evaluation, he expressed a desire to increase his running speed and endurance so that he could compete in recreational races and challenge his post-stroke personal record of 28:15 at the 5 km distance.

Clinical Impression and Examination:

Given his diagnosis of stroke, we were concerned about how residual hemiparesis, gait asymmetries and balance deficits might be affecting his ability to run. His pretest strength and outcome measures are listed in Table 1. Dorsiflexion (DF), hip extension and all other PROM were within normal limits (WNL). Observationally, he walked and ran at greater than normative speeds with reduced arm swing on the affected side. He demonstrated asymmetries in single limb balance and bounding distance onto the unaffected leg. We hypothesized that this was due to interlimb coordination deficits, plantarflexor weakness on the affected limb, decreased power generation on the affected side, decreased load absorption on the affected side and deficits in single limb balance, given that bounding is initiated in single limb stance. He appeared to be a good candidate for coordination, balance, strengthening, power, and high intensity running training (HIT) given his pedigree as an accomplished runner and high motivation to improve his post-stroke 5 km time.

Participant 2

History and Systems Review

The second participant (P2) was a 50-year-old male diagnosed with right hemiparesis from a stroke to the lenticulostriate branches of his left middle cerebral artery 80 months before the evaluation. As a military veteran, he was required to carry heavy loads throughout his career, resulting in numerous lower extremity injuries, which required multiple surgeries to his left foot approximately 15 years prior (e.g., L plantar fasciitis that was treated with a fascial release and platelet rich plasma injections). Before his stroke, he was physically active, weight training in the gym up to four times per week. After the stroke, he had a two week stay in a rehabilitation hospital where he worked on gait training, transfers, stairs, bed mobility and management of ADLs. After inpatient rehabilitation, he was discharged home to live with his supportive wife where he completed an additional 24 months of outpatient physical therapy. He had worked as a project manager but retired early because the diminished function in his R hand prevented him from performing computer related duties required for his job. He noted the presence of R side spasticity, affecting his arm more than his leg. He reported no falls in the six months prior to evaluation. P2 wore a Turbomed XTERN ankle foot orthosis (AFO) daily for R foot drop, and occasionally wore a Bioness Go when hiking on variable terrain. Interestingly, he stated that he despised running before his stroke but once he was unable to run, he was motivated to regain the ability to run. His other goals included developing the strength to play with his dogs outside and to be able to complete yardwork.

Clinical Impression and Examination:

Due to his diagnosis of stroke, we were concerned that hemiparesis, dorsiflexor range deficits, gait and balance asymmetries contributed to his inability to run. His pretest strength and outcome measures are listed in Table 1. DF, hip extension and all other PROM were WNL. P2 had -20 degrees of active dorsiflexion without the XTERN AFO and therefore, we chose to perform all training with the device. Observationally, he walked at a slower than ‘normal’ gait speed, displaying a medial collapse at the affected knee and landing with an audible foot slap. We hypothesized that this was due to poor dorsiflexor eccentric strength/control and hip abductor weakness. He also demonstrated asymmetry in bounding onto the affected leg and we hypothesized that this was due to reduced balance control, reduced power generation on the affected side and the resulting hemiparesis from his stroke contributing to an impaired loading response on the paretic limb. Given his findings, we believed that he would be a good candidate to progress from walking to running with HIT, strengthening, power, and balance training.

Participant 3

History and Systems Review

The third participant (P3) was a 62-year-old female diagnosed with right hemiparesis, ataxia, and dyssynergia resulting from a stroke affecting the right anterior inferior cerebellar artery 24 months before the evaluation. Her past medical history was unremarkable. Before her stroke, she was physically active, running and hiking up to 5 times per week. She has an extensive running pedigree, having completed 41 events at marathon, 50km and 50-mile distances. Writing was her vocation prior to stroke, and she has continued this role in limited capacity after the stroke. After her stroke, she had a two-week stay in a rehabilitation hospital and was discharged home with the support of her boyfriend. She reports that rehabilitation during her stay was limited, with a primary focus on gait training, wheelchair mobility, and basic ADL training. She did not participate in traditional outpatient therapy, although she has involved herself in many clinical research trials over the past two years. At her evaluation session, she noted that she walks on the treadmill twice a week, attends an adult functional fitness class weekly, hikes on single track trails twice weekly, and participates in a tai chi class. She has returned to racing where she walks or hikes in local 5 km, 10 km, and half marathon competitions, but is frustrated by her inability to run. During her evaluation, she reported 3 falls in the past 6 months, all of which occurred while she was hiking ‘technical’ single-track terrain. Her goals were to return to running and increase her speed so that she can participate in 50 km events that offer generous time cutoffs.

Clinical Impression and Examination

Given her diagnosis of cerebellar stroke, we were concerned about residual discoordination and weakness, the presence of gait and balance deficits and how these impairments impacted her inability to run. Her pretest strength and outcome measures are listed in Table 1. DF, hip extension and all other PROM were WNL. Observationally, she demonstrated an ataxic gait while ambulating with a wider base of support and at slower than normal gait speed. We hypothesized that the wider base of support was due to her poor balance (0.71 s in SLS on a solid, flat surface) and the resulting need to increase stability during gait. These balance deficits, along with reduced plantar flexor strength and power generation for push off contributed to her shorter than usual bounding distances onto both the unaffected and affected limb. She appeared to be a good candidate for HIT, strengthening, power, coordination, and balance training to progress from walking to running given her high motivation to return to running.

**Intervention**

To address these functional limitations and impairments, all intervention sessions included a warmup, a running session on either the treadmill or overground, therapeutic exercises to target limb power, coordination exercises, and exercises intended to improve dynamic balance. P1 attended two sessions biweekly for 15 total visits. P2 attended sessions weekly for eight total visits. P3 attended 2-3 sessions weekly for 20 total visits. We developed a comprehensive home exercise program (HEP) for P2 to compensate for his reduced availability to attend in-person sessions. He had access to a home gym and demonstrated adherence to the HEP by his ability to repeat exercises that we introduced to him in the clinic.

All three participants began with a dynamic warmup at the beginning of each intervention session, which consisted of 3 x 20 leg swings in the frontal and sagittal planes for each leg. Because the primary goal for all three participants was to run and improve mobility, we decided to perform high intensity “interval-style” run training.4,16-18 We monitored vitals, including oxygen saturation and heart rate (HR), after each high intensity period to ensure that HR was approximately 70% heart rate reserve (HRR). Timeframes for the high intensity periods were selected based on individual patient response to exercise with respect to tolerance and heart rate. Our participants began training on a treadmill, but we transitioned them to over-ground running as they improved over multiple sessions. Within a given training session, participants first began with a 3-minute warmup at their self-selected comfortable gait speed (CGS). Then, the running intervals began, as the treadmill speed was increased for 30 - 90 s, before returning to CGS for a 3-minute low intensity period. We cycled between the high-intensity and low intensity (recovery) periods for a total of four times within each treadmill training session before concluding with a 3-minute cool-down at CGS. A harness was donned during all treadmill sessions to protect from a fall but did not provide body weight support.

Running sessions were supplemented with strengthening, coordination, power, and agility exercises, which were completed after the treadmill or overground training. A description of exercises, including regressions and progressions can be found in Table 2. Each exercise had a purpose associated with improving running mechanics. For example, all three participants were prescribed the triple flexion/extension drill to improve limb coordination and push off power. Triple flexion/extension drills include simultaneous rapid plantarflexion at the ankle and extension at the knee and hip while the contralateral limb swings through (dorsiflexion at the ankle and flexion at the knee and hip). To increase the capacity for propulsion (take-off limb) and loading response (landing limb) during running, bounding exercises were introduced to all participants. To facilitate propulsive power, all participants performed lower extremity body-weight resistance exercises, including mini-squat jumps and single limb hops. P2 and P3 were prescribed agility drills using a ladder to facilitate a longer step length. P2 and P3 also demonstrated poor dorsiflexion strength and therefore performed toe raises with a focus on controlled, eccentric lowering. To facilitate a controlled, quiet landing, P2 was prescribed step downs from a 9-inch step onto a foam pad. He also demonstrated a medial collapse at the R knee while running, so we provided him with hip abduction exercises (e.g., captain morgans and sidelying hip abduction) to attempt to improve knee control in the frontal plane while running. Finally, P1 engaged in coordination exercises where he tapped color pads placed on a 9-inch step in various sequences with both his heel and his forefoot.

At the beginning of training, P1 was already capable of running, and thus began running at 6.0 mph for 90 seconds. Subsequent high intensity periods within the same treadmill session were progressed to 6.5, 7.0 and 7.5 mph. He eventually plateaued at 8.0 mph during the 7th treatment session and was unable to progress any faster due to an elevated HR response. Given his high performance on the HIT protocol and his desire to run without intermittent walking, an endurance protocol was initiated during his 4th treatment session and was alternated with the high-intensity training protocol for the remainder of the intervention period. The endurance protocol included the same warmup and cooldown periods but incorporated longer periods of running at a lower intensity. The endurance protocol included 3 x 5 minutes at 6.0 mph with an increase in speed to 6.5 mph during the 13th treatment session when 6.0 miles per hour no longer sufficiently challenged his cardiovascular response. P1 transitioned to overground running in the 7th session where he ran 8 x 240 feet without any foot scuffs or loss of balance.

P2 walked on the treadmill during his 1st treatment session as he alternated between his comfortable and fastest possible walking speeds. During the second session, however, P2 began running on the treadmill but required the use of his unaffected hand on the treadmill rail for balance support during HIT periods. He was encouraged to progressively reduce reliance by first using only three fingers, then one finger and finally, hovering his hand over the rail, only touching down if he felt like he could not self-correct. By the 3rd treatment session, he no longer required handrail support. During all subsequent sessions, he tolerated 2 x 60s at 3.6 mph followed by 2 x 60s at 3.8 mph during the HIT periods, except for session 7 where he ran at 4.4 mph 6x for 10-15 seconds followed by a 2-minute recovery period at CGS. He demonstrated more scuffs at this speed and required verbal cues to drive his affected leg through the swing phase to assist in foot clearance. P2 ran with an XTERN AFO but demonstrated poor dorsiflexor eccentric control during loading response as he landed with an audible and visible foot slap on the affected side. Verbal cues were used to facilitate a quieter landing. A full-length body mirror was also positioned in front of the treadmill to provide visual feedback. During the 8th session, P2 progressed to overground running where he ran 120 feet eight times and 240 feet four times with zero scuffs and no loss of balance. Each bout of overground running was separated by a 2-minute rest period.

P3 had an extensive fall history due to her hobbies of hiking over variable terrains. She also had a negative experience on a treadmill in her community gym where she had fallen off and was unable to stop the belt. For these reasons, P3 demonstrated fear avoidance behavior during our initial treadmill training. To demonstrate the functional safety features of the harness, P3 was instructed to voluntarily fall back in the harness before each treadmill session. P3 began treadmill training walking at 2.0 mph during HIIT periods with a recovery period at 1.8 mph. She required the use of both handrails for support during the recovery periods for heart rate recovery. Early treatment focused on establishing comfort on the treadmill without requiring handrail support for balance. By the third session, she progressed to walking at 2.4 mph during the HIIT period but required continued handrail support, and consistently scuffed the treadmill but was able to self-correct without falling. Verbal cues to lift her knee and her toes were used to assist with foot clearance. A mirror was placed in front of the treadmill to provide visual feedback. By the 6th session, HIIT bouts progressed to 3.0 mph and she no longer required handrail support although she was still unable to achieve a period of double float. During the 11th session, the HIIT protocol was adjusted to include short bouts of high intensity running (10s) at 4.4 mph to facilitate a period of double float. She was able to achieve double float at these speeds but required the use of bilateral handrail support. During the 13th treatment session, she progressed to overground running, completing four bouts of 250 feet, but required the use of a trekking pole in her L hand to assist with R push off. To achieve periods of double float, we used verbal cues to help her coordinate trekking pole and R foot push-off.

P3 was recommended the Altra Lone Peak 6 shoe, which is minimalist in design with zero heel stack. She was previously wearing a shoe with an 8 mm heel stack, placing her foot in a more plantarflexed position. This may have contributed to her inadequate foot clearance during treadmill training, resulting in more scuffs and an increased fall risk. The sole of the Altra shoe is also thin which we hypothesized may enhance sensory feedback as she enjoys hiking single track trails with variable terrain. She wore this shoe from her 3rd session onwards.

**Outcomes**

All participants repeated testing at 3 months. All clinical outcome measures are shown in Table 3.

P1 improved his running velocity from 3.1 m/s to 3.28 m/s. P2 was able to run after the intervention period at 2.41 m/s with a double float period of 7.57% of running gait cycle. P3 was unable to run without an assistive device, but achieved a period of double float with the assistance of a trekking pole. However, she improved her FGS to 1.84 m/s. P1 and P3 improved their 6MWT although all changes were within the MDC for chronic stroke (120 feet).20

All three participants improved their HiMAT score. P1 improved by 4, P2 improved by 5 and P3 improved by 1 point. Although an MDC does not exist for chronic stroke, P1 and P2 improved by at least 4 points which is the MDC95 for chronic TBI populations.21 P2 and P3 demonstrated large improvements in bounding distance onto both the affected and unaffected legs suggesting that power generation and loading response improved. P1 demonstrated comparatively small improvements in bounding bilaterally, perhaps due to a ceiling effect given his impressive pre-training bounding distance.

Despite our attempts to improve balance during training, the changes in balance measures were not as dramatic as the gait and high-level mobility outcomes. For P2 and P3, SLS and the miniBESTest improved or declined slightly. However, P1 improved his miniBESTest score by 4 points and improved SLS balance on firm surface by 16.67 (unaffected) and 17.4 seconds (affected). We likewise saw only small changes in strength, although P2 increased DF strength on his affected side to achieve a limb symmetry index of 80.9%.

At the completion of training, all participants noted improvements in high level mobility. P1 set a post-stroke personal record at the 5 km distance in 28 minutes, beating his previous time by 45 seconds on a course that he claimed to have a greater vertical gain profile than the previous course. P2 stated that he was ecstatic at his ability to run because he thought he would never be able to run after his stroke. Additionally, he claimed that he was now able to chase his dogs in his backyard. P3 reported improved ability to navigate single track trail without falls as she no longer holds on to her boyfriend for support. Furthermore, she set a 5 km personal record by 2 minutes and is now able to participate in events of longer distances. She recently placed 3rd in her age group at a single-track trail half marathon in a time of 7 hours, beating her previous years’ time by nearly 1.5 hours.

Table 1: Pre-test Strength Measures

|  |  |  |  |
| --- | --- | --- | --- |
| Test/Measure | P1 | P2 | P3 |
| PF torque limb symmetry (%) | 88.11 | 41.99 | 105.25 |
| DF torque limb symmetry (%) | 86.12 | 28.92 | 82.60 |
| Knee flex torque limb symmetry (%) | 97.53 | 61.75 | 78.73 |
| Knee ext torque limb symmetry (%) | 83.43 | 92.06 | 98.05 |
| Hip flex torque limb symmetry (%) | 122.10 | 115.68 | 70.41 |
| Hip ext torque limb symmetry (%) | 95.12 | 87.05 | 94.06 |

Table 2: Exercise chart (not included d/t formatting issue)

Table 3: Pre- and Post-test Outcome Measures

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Test/Measure | P1 | | P2 | | P3 | |
|  | Pre | Post | Pre | Post | Pre | Post |
| 6MWT (ft) | 2,278 | 2347 | N/a\* | 1650 | 1,562 | 1610 |
| HiMAT | 30 | 34 | 15 | 20 | 14 | 15 |
| Bound to Affect (cm) | 99.82 | 106 | 26.035 | 86.67 | 8.33 | 68.83 |
| Bound to Unaffect (cm) | 32.18 | 33 | 55.88 | 63.67 | 6.33 | 49.33 |
| SLS affected (flat ground, eyes open) (s) | 2.6 | 20 (max) | 9.71 | 4.85 | 0.71 | 1.15 |
| CGS (m/s) | 1.62 | 1.54 | 1.1 | 1.30 | 1.28 | 1.37 |
| FGS (m/s) | 2.1 | 2.04 | 1.77 | 1.58 | 1.67 | 1.84 |
| Run (m/s) | 3.1 | 3.28 | Unable | 2.41 | unable | unable |

\*not tested during pre-test due to presence of HTN at baseline testing.

Discussion:

Our participants were able to run after focused training, demonstrating that running is possible for some individuals after stroke. Notably, we observed a range of running abilities at baseline, yet all three participants showed subjective and objective improvements in running ability and met many of the goals they had created for themselves prior to training. Despite the different running abilities, we employed an overarching framework to guide our rehab, focused on high-intensity interval training, targeted strength training, and high velocity movements. We believe that this approach can be used to guide running training for some people with stroke, and we speculate that independent bilateral bounding and self-selected comfortable gait speeds > 1.0 m/s are predictive of who may have the capacity to run.

**Application of Walking Intervention Parameters to Run Training**

Given many of the inherent similarities between walking and running, we chose to adopt many successful principles from the literature regarding walking retraining for people post-stroke. Specifically, when selecting exercise parameters, we used past literature for guidance on FITT (Frequency, Intensity, Time, and Type) parameters. A recent set of Clinical Practice Guidelines recommended the use of task specific practice (walking) be performed 2 to 3 times per week, for 1 to 1.5 hour sessions, over the duration of 1 to 6 months.4 Those authors also suggested the use of moderate to high intensity (i.e., > 60% HRR) walking to increase walking speed and distance after stroke.4 Boyne and colleagues have shown that a short-interval HIIT program can produce greater walking capacity gains than walking at a moderate intensity at 8 and 12 weeks with no apparent plateau.18 Given the respective improvements in walking function, we adopted these parameters for our running program.

The relative value of training at higher intensities may be multifactorial. For example, the greater neuromuscular activity required in high intensity efforts is necessary to support the increased running speeds.4 Furthermore, vigorous HIIT has shown increases in brain-derived neurotropic factor, corticospinal excitability, and intracortical inhibition when compared to moderate intensity exercise.22 Thus, high intensity efforts may have facilitated motor learning, and promoted the necessary neuromuscular capabilities required to support running.

**Application of a Conceptual Framework**

We based our training approach broadly on that of Williams and Schache, who introduced a conceptual framework to guide interventions for return to running after TBI.13 Their framework was based on the sequential production of higher-level tasks, and was guided by the biomechanics associated with typical running gait. In particular, they promote the use of the HiMAT to grade the patient on a continuum of higher-level tasks so that the next mobility goal can be established. Similarly, we primarily used the HiMAT to inform intervention selection for targeted impairments that may impact running ability. For example, all three participants had difficulty with bounding and thus, bounding variations were prescribed to all participants. We believe that bounding formed an important component to our intervention, as it encompasses a strong push off, a period of double float, and load absorption, all of which are necessary for running.

Combining the knowledge of an individual’s force production capability and the kinetics necessary to support running can be used to guide intervention selection. We used a 3D movement analysis and muscle testing using handheld dynamometry to assess joint kinetic data during functional tasks and isolated static situations. Assessment of lower limb joint torques and powers identified weak muscle groups and ultimately, informed our intervention selection. For example, P2 had a dorsiflexor torque limb symmetry index of 28.9% which was contributing to poor load absorption and foot slap, so a component of his strengthening program included dorsiflexor strengthening. We suggest using kinetic data to develop individualized intervention plans aimed at treating specific impairments that limit running ability.23

High velocity lower limb power training has been used to elicit faster walking speed after stroke.19 Ballistic training optimizes power generation for propulsion by balancing load and velocity.23 Power is described as push off and load absorption in the context of walking gait and the high angular velocities that occur during walking suggest that power generation and absorption occur rapidly.23 Given that angular velocities are even greater in running, we included exercises focused on high velocity concentric and eccentric contractions, such as split squat jumps, triple extension/flexion drills, hopping, and bounding. We believe that an increase in lower limb power is necessary to sustain both propulsion and weight acceptance, which are critical biomechanical components associated with running. These exercises were just as important as actual running and we suggest a multidimensional intervention approach focused on power, strength, balance and running.

**Feedback**

We believe that our use of feedback helped our participants improve their running technique during training. Feedback is known to enhance motor learning during gait training post-stroke.24 We therefore used verbal feedback during both treadmill and overground training to improve within and across session retention. P2 and P3 had difficulty swinging the affected leg through at higher speeds resulting in asymmetrical stride times. Increased stride time variability impacts the accuracy and consistency of gait coordination of the lower limbs after stroke increasing both fall risk and fear of falling.25 We found that verbal cues to “swing your leg through” and “reach out further with your affected leg” had good carryover in decreasing gait variability. P2 and P3 also had difficulty clearing the foot during swing phase causing scuffs and loss of balance. “Lift your toes” and “swing your hip through” both appeared to improve toe clearance and reduce the number of scuffs. P2 demonstrated foot slap due to his weak dorsiflexors. Cues to “land quietly” appeared to lessen the amount of foot slap. When P3 made the transition from fast walking to running on the treadmill, she showed a positive response to “faster steps” and “quicker steps” to increase cadence. In addition to verbal cues, we also positioned a mirror in front of the treadmill to provide visual feedback and to reinforce the verbal cuing we provided.

**AD/AFO use**

Given the variability in motor deficit after stroke, many patients use an assistive device or an AFO for support of the body, or individual joints. These devices and braces are commonly associated with supporting lower functional activities, yet many patients who use such devices may still have the goal of returning to higher level activities like running. Interestingly, we found success in the use of both assistive device and AFO use in returning to running post-stroke. For example, P2 used the TurboMed XTERN foot drop orthotic during all HIIT and overground running sessions, demonstrating that it is possible to run with an AFO. We can speculate that he would not have been capable of running without his AFO. Furthermore, P3 demonstrated reduced push off power which appeared to prevent her from running. With the use of a trekking pole on the unaffected side, however, she was able to generate enough push off to allow her to achieve double float and meet the definition of running. She required training on the synchronization of push off output which may have been more difficult for her given coordination deficits following cerebellar stroke.

**Race Participation Considerations**

P1 and P3 participated in racing events during the study which may have motivated them during treatment sessions and to comply with home exercise prescription. P1 was excited to break his personal record at the 5k distance. P3 wanted to participate in longer distance trail events. Both P1 and P3 had unprompted goals that were driven by their passion for running before participating in this study. Racing is rewarding because it provides an opportunity to measure success against past results. It is uncharacteristic of a runner to be satisfied in breaking a personal record just once. Rather, the aim now shifts to how they can break the newly established record. Thus, racing provides an opportunity for continuous assessment outside of the clinic. Through rehabilitation in the early stages of recovery of running, therapists offer the patient the opportunity to reach independence where improvements are made through unsupervised practice. This allows the patient to continue to reap all the social and health rewards that come with running long after discharge from therapy services.

One limitation of our study is low external validity across stroke given that it is a case series with a small sample size.

Conclusion

Running is possible for some after stroke. P1 was able to participate in community races, P2 was able to run with his dogs in his yard, and P3 was able to complete long distance endurance events. Perhaps these stories are more important than any other result as return to running after stroke is clearly meaningful to the patient.

References:

1. Mehta S, Pereira S, Viana R, et al. Resistance training for gait speed and total distance walked during the chronic stage of stroke: a meta-analysis. *Top Stroke Rehabil*. 2012;19(6):471-478. doi:10.1310/tsr1906-471
2. Langhorne P, Coupar F, Pollock A. Motor recovery after stroke: a systematic review. *Lancet Neurol*. 2009;8(8):741-754. doi:10.1016/S1474-4422(09)70150-4
3. Mehrholz J, Thomas S, Elsner B. Treadmill training and body weight support for walking after stroke. *Cochrane Database Syst Rev*. 2017;8(8):CD002840. doi:10.1002/14651858.CD002840.pub4
4. Hornby TG, Reisman DS, Ward IG, et al. Clinical practice guideline to improve locomotor function following chronic stroke, incomplete spinal cord injury, and brain injury. *J Neurol Phys Ther*. 2020;44(1):49-100. doi:10.1097/NPT.0000000000000303
5. Spencer T, Aldous S, Williams G, Fahey M. Systematic review of high-level mobility training in people with a neurological impairment. *Brain Inj*. 2018;32(4):403-415. doi:10.1080/02699052.2018.1429656
6. Thordarson DB. Running Biomechanics. *Clin Sports Med*. 1997;16(2):237-247.
7. Dugan SA, Bhat KP. Biomechanics and analysis of running gait. *Phys Med Rehabil Clin N Am*. 2005;16(3):603-621. doi:10.1016/j.pmr.2005.02.007
8. Novacheck TF. The biomechanics of running. *Gait Posture*. 1998;7(1):77-95. doi:10.1016/S0966-6362(97)00038-6
9. Lattouf NA, Tomb R, Assi A, Maynard L, Mesure S. Eccentric training effects for patients with post-stroke hemiparesis on strength and speed gait: A randomized controlled trial. *NeuroRehabilitation*. 2021;48(4):513-522. doi:10.3233/NRE-201601
10. Fong KN, Chan CC, Au DK. Relationship of motor and cognitive abilities to functional performance in stroke rehabilitation. *Brain Inj*. 2001;15(5):443-453. doi:10.1080/02699050010005940
11. Devetak GF, Bohrer RCD, Rodacki ALF, Manffra EF. Center of mass in analysis of dynamic stability during gait following stroke: A systematic review. *Gait Posture*. 2019;72:154-166. doi:10.1016/j.gaitpost.2019.06.006
12. Miller EW, Combs SA, Fish C, Bense B, Owens A, Burch A. Running training after stroke: a single-subject report. *Phys Ther*. 2008;88(4):511-522. doi:10.2522/ptj.20050240
13. Williams GP, Schache AG. Evaluation of a conceptual framework for retraining high-level mobility following traumatic brain injury: two case reports. *J Head Trauma Rehabil*. 2010;25(3):164-172. doi:10.1097/HTR.0b013e3181dc120b
14. Yahya T, Jilani MH, Khan SU, et al. Stroke in young adults: Current trends, opportunities for prevention and pathways forward. *American Journal of Preventive Cardiology*. 2020;3:100085. doi:10.1016/j.ajpc.2020.100085
15. Williams GP, Morris ME. High-level mobility outcomes following acquired brain injury: a preliminary evaluation. *Brain Inj*. 2009;23(4):307-312. doi:10.1080/02699050902774170
16. Boyne P, Scholl V, Doren S, et al. Locomotor training intensity after stroke: Effects of interval type and mode. *Top Stroke Rehabil*. 2020;27(7):483-493. doi:10.1080/10749357.2020.1728953
17. Boyne P, Doren S, Scholl V, et al. Preliminary Outcomes of Combined Treadmill and Overground High-Intensity Interval Training in Ambulatory Chronic Stroke. *Front Neurol*. 2022;13:812875. doi:10.3389/fneur.2022.812875
18. Boyne P, Billinger SA, Reisman DS, et al. Optimal intensity and duration of walking rehabilitation in patients with chronic stroke: A randomized clinical trial. *JAMA Neurol*. Published online February 23, 2023. doi:10.1001/jamaneurol.2023.0033
19. Morgan P, Embry A, Perry L, Holthaus K, Gregory CM. Feasibility of lower-limb muscle power training to enhance locomotor function poststroke. *J Rehabil Res Dev*. 2015;52(1):77-84. doi:10.1682/JRRD.2014.04.0109
20. Flansbjer U-B, Holmbäck AM, Downham D, Patten C, Lexell J. Reliability of gait performance tests in men and women with hemiparesis after stroke. *J Rehabil Med*. 2005;37(2):75-82. doi:10.1080/16501970410017215
21. Williams GP, Greenwood KM, Robertson VJ, Goldie PA, Morris ME. High-Level Mobility Assessment Tool (HiMAT): interrater reliability, retest reliability, and internal consistency. *Phys Ther*. 2006;86(3):395-400. doi:10.1093/ptj/86.3.395
22. Boyne P, Meyrose C, Westover J, et al. Exercise intensity affects acute neurotrophic and neurophysiological responses poststroke. J Appl Physiol. 2019;126:431-433. Doi:10.1152/japplphysiol.00594.2018
23. Williams G, Hassett L, Clark R, et al. Improving Walking Ability in People With Neurologic Conditions: A Theoretical Framework for Biomechanics-Driven Exercise Prescription. *Arch Phys Med Rehabil*. 2019;100(6):1184-1190. doi:10.1016/j.apmr.2019.01.003
24. Rendos NK, Zajac-Cox L, Thomas R, Sato S, Eicholtz S, Kesar TM. Verbal feedback enhances motor learning during post-stroke gait retraining. *Top Stroke Rehabil*. 2021;28(5):362-377. doi:10.1080/10749357.2020.1818480
25. Patel P, Enzastiga D, Casamento-Moran A, Christou EA, Lodha N. Increased temporal stride variability contributes to impaired gait coordination after stroke. *Sci Rep*. 2022;12(1):12679. doi:10.1038/s41598-022-17017-1