Effect of an intensive strengthening, agility and body weight supported treadmill training program on running outcomes in individuals with traumatic brain injury

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ABSTRACT

Introduction: The re-introduction of high level mobility tasks such as running in individuals with traumatic brain injury currently has a limited literature base. Re-learning to run may enable this population to maintain a healthier lifestyle by increasing participation in recreational and sport-related activities. *Methods:* Five individuals with a traumatic brain injury participated in a 15 week program to re-learn running mechanics. This program included strength, agility, and balance training; running with body-weight supported treadmill training; and over-ground running and high level sport-specific drills. Dependent variables included strength, running speed, running distance, quality of running, high level mobility, and quality of life.

Results: Participants demonstrated significant improvements in running speed and high level mobility, with evidence beyond measurement error ($p < 0.05$). Individual changes in running distance were found for all but one participant, however statistically significant improvements were not identified. There were observable changes in running quality for each participant in the final gait analysis. Strength changes were found to be inconsistent. *Discussion:* The significant improvements noted in this study for running speed, high level mobility, and changes in quality of gait are consistent with those found in the current literature. The individualized, intense, and specific training protocol used in this study elicited neuroplastic changes in the adult brain, leading to the significant improvements that were noted. *Conclusion:* Individuals with chronic TBI have the potential to learn to run again and improve running speed, high level mobility, and running quality through participation in an individualized, high-intensity mobility training protocol.

Suggested Keywords: brain injury; body weight support; dynamic exercise; sport-specific training; High Level Mobility Assessment Tool

INTRODUCTION

Traumatic brain injury (TBI) is a broad term used to classify damage to the brain following a direct impact to the skull or a diffuse axonal injury.[1] A traumatic brain injury can range in severity from mild to severe, depending upon the type of trauma, length of unconsciousness, age, and level of prior function.[2] Developing an appropriate plan of care for a individual in the ICU, hospital, rehabilitation facility, or outpatient clinic is dependent upon many of these factors and will influence the type of rehabilitation techniques that are used. The acute phase of rehabilitation focuses primarily on bed mobility[3] and cognitive/sensory training,[4,5] later progressing to gait training[6] and functional re-education.[7,8] Structured rehabilitation for persons diagnosed with a TBI is usually discontinued once they have attained independence with functional mobility, at which point these individuals are encouraged to resume typical activities of daily living. There is considerable variability in the functional outcomes of persons recovering from TBI after returning home and there are few programs available for individuals to continue physical therapy to facilitate the return to recreational and sports specific activities.

Rehabilitation for a traumatic brain injury is tailored to minimize the impairments and functional limitations that are unique to each individual. Common physical limitations for individuals in both the acute and later stages of recovery from a TBI include contralateral strength deficits,[9,10] fluctuating muscle tone,[9] disorganized movement,[11] impaired balance,[9,10] and deviated gait.[9,12,13] Cognitive and behavioral deficits resulting from TBI also contribute to significant disability in returning to daily social, recreational, and occupational activities.[14] Typical hospital rehabilitation programs for individuals recovering from TBI include sensory stimulation,[4,5] serial casting,[15-17] aerobic training,[18] and functional training.[7,8] These rehabilitation strategies for individuals in the inpatient setting help promote return to activities of daily living (ADLs) and instrumental activities of daily living (IADLs), however they do not prepare individuals for participation in higher level activities, such as sports.

Running is the cornerstone for many individual and team sports and recreational activities, and has been reported to be a significant challenge for individuals following a TBI. Individuals in the post-recovery stage of TBI frequently discontinue membership in sports and recreational activities that require speed and agility due to deficits in running ability.[19] The cognitive, proprioceptive, and physical impairments that linger throughout the “return to function” phase of TBI recovery likely attribute to both the apprehension and lack of confidence in running capabilities.

Walking and running are two kinetically similar but distinctly different gait patterns. Walking consists of alternating periods of double and single leg support where the body is propelled forward by “vaulting” in an arc up and over a planted leg.[20] Running is an even more complex biomechanical process, consisting of a period of stance, swing, and “flight,” where both legs are no longer in contact with the ground.[19-21] When compared to walking, running consists of a lesser amount of ground contact time, greater ground reaction force, increased step length and cycle duration, and decreased stance duration.[20,22] Many of these changes in the transition from walking to running may be attributed to alterations in the intensity of muscle activation and timing.

Walking requires recruitment of the tibialis anterior muscle prior to toe-off and activation of the anterior muscles is maintained throughout the swing phase. Posterior muscles including the gastrocnemius-soleus complex are activated at 40% of the walking cycle. Running amplifies muscle activation of the tibialis anterior during the middle of the gait cycle and produces greater levels of calf muscle activity at the point of heel strike.[20] The intensity of muscle activation is associated with the timing of foot strike during walking and running. Foot strike occurs when the posterior surface of the heel comes in contact with the floor during walking and when the forefoot touches the floor during running.[20] Differences in the gait cycle are also present during the stance phase of running, which requires earlier and more vigorous activation of the ankle extensors, improved balance and proprioception, and greater range of motion of the hip, knee, and ankle.[20,21] In addition, running requires increased activation of proximal leg and trunk musculature when compared to walking.[20] Cumulatively, the disparities between walking and running contribute to the challenges that individuals recovering from a TBI may face when attempting to run again.

Individuals diagnosed with a TBI characteristically demonstrate marked unilateral weakness in dorsiflexors[11,23] paired with deficits in ankle stability[20,21] and proximal control.[20] These impairments result in poor control of the ankle, lower leg, and trunk during the stance phase of gait, and consequently may lead to an increased risk for falls. Frequently identified gait deviations include equinovarus, toe curling, excessive hip and knee flexion, “scissoring” gait, and “stiff-knee” gait.[11,12] Each of these gait deviations, presenting solely or collectively, contribute to deficits in balance and safe ambulation. Impaired balance and coordination are primary concerns following a TBI, with as many as 30% reporting these deficits.[24,25]

Walking and running require a combination of sensory, motor-programming, and musculoskeletal systems, all of which are typically disrupted in persons with a TBI. Modifications in normal biomechanical components of stability, including changes in the position of center of mass, can contribute to significant static and dynamic balance deficits. Individuals diagnosed with a TBI typically experience a shift in their center of mass to a position lower anteriorly and posteriorly and higher medially and laterally. Consequently, these individuals are more likely to experience a significant degree of sway during ambulation and rely primarily on visual input from the environment to maintain balance.[26,27] Dynamic balance in persons diagnosed with TBI is influenced by differences in temporal spatial characteristics of gait when compared to those without a neurological diagnosis. Abnormal gait is the result of the reliance on poor visual processing paired with impaired somatosensory processing. These individuals typically ambulate using a slower walking speed and shorter stride length to compensate for balance issues related to dysfunction of these systems.[12,27]

Functional limitations are compounded by a hemiplegic gait pattern and asymmetrical balance response when exposed to perturbations from the environment.[28] As a result, more time is spent in stance on the unaffected lower extremity. These specific gait deficits present similarly to those diagnosed with a stroke, with the stance phase consisting of 80% of time on the unaffected limb and 70% of time on the affected limb.[12] Evidence suggests that persons with a TBI have difficulty maintaining balance and stability in the frontal plane and are sometimes unsuccessful controlling movement while stepping over obstacles,[28] which when paired with slowed reaction times may translate into challenges with walking and running safely without falling.[29] Additionally, deficits in core and lower extremity stability may hinder running efficiency, causing over-activation of trunk and extremity muscles, and ultimately preventing safe ambulation.[20] Deviated gait, decreased strength, poor coordination, and impaired balance that many persons diagnosed with TBI experience contribute to instability during ambulation, an increased risk of falls, and subsequent injury.

Physical therapy programs are designed to help individuals with a TBI increase strength and improve functional abilities while maintaining a safe environment that will minimize the risk of falling. Body weight supported treadmill training (BWSTT) consists of a harness and lift mechanism that is used to support an individual over a treadmill for safe ambulation especially if he/she is unable to maintain the appropriate postural control, strength, ROM, or speed to walk or run without assistance.[30,31] The spinal cord can generate efferent motor patterns that enable independent automatic stepping in the absence of normal supraspinal input.[32,33] This automatic stepping pattern is generated only after individuals reach a certain walking speed, bear weight through the lower extremities, and maximize available hip extension for propulsion. Use of BWSTT helps individuals to achieve optimal body and joint positioning so that speed of locomotion can be increased and a more automatic stepping pattern can be achieved.[32]

This apparatus has been used in the rehabilitation of individuals following a stroke or a TBI to improve several components of overground walking, including functional balance, speed, and endurance.[30,34-38] Individuals following a stroke demonstrate similar impairments to those persons diagnosed with a TBI, and as a result, rehabilitation techniques coincide. The evidence suggests that the use of BWSTT either solely or paired with a resistive strengthening and aerobic program for individuals following a stroke yields improvements in walking velocity,[36,37] distance,[36,37,39] cadence,[36] stride length,[36] amplified lower extremity muscle activation,[36,39] balance,[39] and improved gait symmetry.[40]

Similarly, individuals diagnosed with a TBI demonstrate improvements in gait parameters such as distance, speed, level of assistance required for ambulation on treadmill, and extremity strength.[34,35] Scherer [35] investigated the use of BWSTT in a 36 year old male soldier following a TBI from a blast injury on gait outcomes. At the completion of the study, this individual demonstrated gains in six minute walk distances, Missouri Assisted Gait scores, and maximum distance ambulated. Additional case studies have demonstrated gains in the level of ambulatory independence following a rehabilitation program including BWSTT in persons four years and four months post-TBI.[41] Implementation of an exercise program using BWSTT in individuals with a TBI has also yielded improvements in cardiovascular variables. Mossberg [42] implemented a BWSTT walking program lasting 11-15 weeks in persons with TBI. The results showed that peak oxygen uptake increased 16-24%, estimated cardiac stroke volume improved 26-32%, and total treadmill work grew 53-134%, indicating that BWSTT is an effective intervention for this population to improve cardiovascular outcomes as well as total walking time.

Within the past few years, two randomized controlled trials have been performed that suggest BWSTT as a plausible treatment modality for individuals diagnosed with TBI. Wilson [6] investigated the effectiveness of an 8 week BWSTT program twice weekly vs. traditional physical therapy in persons with TBI in the inpatient setting. All participants demonstrated improvements in the Functional Ambulation Category, Standing Balance Scale, Rivermead Mobility Index (RMI), and Functional Independence Measure (FIM). However, both treatment protocols demonstrated equivalent improvements in these variables, suggesting that use of either treatment approach is effective in improving clinical outcomes in individuals in the acute stages of rehabilitation following TBI. Another study compared the use of BWSTT and conventional overground-gait training (COGT) in individuals diagnosed with TBI, finding that COGT is more effective in improving gait symmetry than BWSTT.[34] Although improvements were found in gait parameters in persons participating in BWSTT and COGT, the results suggest that individuals who wish to initiate a treadmill walking program should include an overground walking component.

More recently, BWSTT has been used with individuals diagnosed with a TBI striving to run again to return to recreational and sports specific activities. Moriello [31] documented outcomes following the implementation of a program consisting of strength training, BWSTT, and overground ambulation over a period of 38 weeks on running quality and lower extremity strength. The findings indicate that BWSTT paired with strength training may have improved running endurance and speed, increased lower extremity strength, and facilitated return to participation in physical education classes in a person with TBI. Another study conducted by Williams,[43] recruited individuals diagnosed with a TBI to participate in a high level mobility program spanning a period of three months. The protocol included a combination of dynamic strengthening exercises, agility drills, and home exercises. The results demonstrated significant gains in high level functional mobility, which suggests that the optimal treatment regime to prepare for overground running may consist of a blending of BWSTT, dynamic strengthening, and agility training in order to ensure that all components of running are practiced.

Improvements in functional activities and components of running have also been found in individuals with neurological diagnoses other than TBI. Miller [44] investigated the benefits associated with an 8 week BWSTT program in a 38 year old male two and half years following a stroke. The results showed that single leg balance, step width, and sprint speed improved significantly from baseline, demonstrating an overall 10% improvement in running variables. Similar outcomes in gait speed have been found after implementing a 6 week walking/running program using BWSTT with a 28 year old male 7 months following a C5/C6 incomplete spinal cord injury. The findings revealed an increase in normal walking speed (1.22 to 1.37 m/s), fast walking speed (1.63 to 1.8 m/s), and running speed (2.64 to 3.24 m/s) at the completion of the study.[45] There are definitive gaps in this area of research, however the existing evidence suggests that using BWSTT in conjunction with other treatment methods may help individuals following a TBI run again safely and efficiently.

A comprehensive exercise program designed to improve global functioning and running ability should utilize a multi-dimensional approach to maximize functional outcomes. Resistance exercise is frequently incorporated into the training programs of many athletes striving to improve running ability. The evidence suggests that trained runners demonstrate gains in lower extremity strength after supplementing a typical running program with a 10 week resistance training regime.[46,47] Exercises such as squats, knee extensions, knee flexions, and toe raises are frequently included in these protocols.[47] Similar programs, including plyometric training, have also been shown to be effective in improving running economy, which has been defined as the oxygen required to run at a given intensity. Paavolainen [48] utilized a 9 week high velocity plyometric program that was found to improve running economy and muscle power in distance runners, yielding a 3.1% increase in 5K running speed. These results may be attributed to improvements in lower extremity and core strength, muscle coordination,[49] and muscle co-activation around lower extremity joints.[50] Incorporating agility and resistive activities into a running program may help maximize muscle strength and power and ultimately enhance overall running performance.

Currently, few studies have been published investigating the changes in running quality, speed, endurance, and strength after implementing a training program incorporating the use of BWSTT and strength and aerobic training in a group of individuals living with a TBI. The purpose of this study is to identify the differences in functional mobility, lower extremity strength, running distance, running speed, running quality, and quality of life following an intensive endurance, strengthening, and flexibility program paired with BWSTT.

METHODS

Participant One

The first participant was a high-school student who sustained a TBI during a baseball accident four years prior to the study. After emerging from a two month coma, he progressed through sub-acute rehabilitation and subsequently participated in physical therapy at home and in the school setting. At the beginning of this study, he had been receiving therapy once weekly at a local rehabilitation hospital, and was still attending therapy at school three times weekly. He had tried running, but had fallen several times.

His past medical history (PMH) included a left foot and ankle fracture (two years prior to the study), as well as low back pain and frequent headaches. Additionally, he had poor circulation in his lower extremities, decreased peripheral vision in his left eye, depression, and re-occurring falls. He had a history of seizures immediately following the accident. He had also been receiving Botox injections in his left arm every three months, which his parents stated was effective.

At the time of the study, he ambulated community distances without an assistive device and was independent with bed mobility, transfers, and stairs. An ankle foot orthotic (AFO) was constructed and fitted for his left ankle, but he chose not to wear it at school because he felt it was uncomfortable.

Initial evaluation findings revealed decreased bilateral hip flexor passive range of motion (PROM) and impaired muscle length of bilateral hamstrings (left greater than right). He presented with decreased strength throughout his left upper extremity, as measured with manual muscle testing (MMT), as well as a marked decrease in strength of the left lower extremity as compared to right as measured by hand held dynamometry (HHD). See Tables 1-3 for details of PROM and strength testing.

Superficial, deep, and combined cortical sensation was all noted to be within normal limits (WNL). Cranial nerve testing was WNL except for the presentation of abnormal nystagmus and delayed vestibular-ocular reflex (VOR). Tone was noted to be normal throughout, with the exception of a mild increase in left ankle plantarflexor tone. An abnormal flexor synergy pattern was noted on the right coinciding with maximal effort during the examination. Deep tendon reflexes were absent throughout. Coordination testing displayed mild to moderate impairments throughout the left upper and lower extremities. See Table 4 for details of coordination testing.

The participant demonstrated normal static and dynamic sitting balance, but decreased static and dynamic standing balance. Observational gait analysis revealed decreased trunk rotation, as well as decreased arm swing and heel strike on the left, and increased external rotation of the hip on the left. These gait deviations were magnified when he was asked to run, for which he needed close supervision. This participant fell during the running component of the initial evaluation, which resulted in a sprained wrist. His initial High Level Mobility Assessment Tool (HiMAT) score was 4/52.

Prior to the injury, this individual was independent with all ADLs, IADLs, recreational activities, and functional mobility. This individual’s baseline Satisfaction with Life Scale (SWLS) score was 25/35, and his main goal for this program was to be able to safely run two-hundred feet so that he could get back to playing baseball.

Participant Two

Six years prior to the start of the study, our second participant had experienced a TBI and a mandibular fracture due to a car accident, after which she was in a coma for about three weeks. After 16 weeks of acute care at 2 different hospitals, she was transferred to a rehabilitation hospital for 3 months, and continued with outpatient physical therapy for 2 years. This individual was visiting the gym three times weekly to use the arc trainer and the leg press at the start of the study.

She was independent with all ADLs and IADLs except driving, and was unemployed. She was also independent with all transfers, stairs, and ambulation over community distances without a device.

Her past medical history was significant for Crohn's disease, bilateral ankle fractures, shingles, anemia, delusional disorder, and hypothyroidism. This individual stated that both her vision and her memory had declined since the accident. She reported occasional pain near the left lateral malleolus, as well as in the left shoulder during end-range PROM. She was limited in left shoulder internal rotation. Bilateral hamstring muscle length was impaired to sixty degrees. Bilateral lower extremity strength was WNL, while upper extremity strength was limited, especially in the left. See Tables 5-7 for PROM and strength details.

Sensation testing revealed intact results throughout bilateral upper and lower extremities for superficial, deep, and combined cortical systems, with the exception of slight difficulty with stereognosis on the left. Cranial nerve testing was WNL, except her eye movements were noted to have decreased velocity. She demonstrated fluctuating tone and mild synergistic patterns in left upper and lower extremities during active movements. Deep tendon reflexes were hyperreflexic throughout the left upper and lower extremities. She also had moderately impaired coordination throughout the left upper and lower extremities, with the exception of the finger-to-nose test. See Table 8 for details of coordination testing.

She was able to maintain single-leg-stance for ten seconds on the right, but only four seconds on the left. Gait analysis while walking revealed hyperextension of the left knee during stance, decreased weight-bearing on the left, and mild left foot drop. While running ten feet with contact guard, decreased weight-bearing on the left side and decreased coordination during swing phase were noted. Her HiMAT score at baseline was 25/52.

Prior to her TBI, she was independent with all activities and enjoyed running long distances. Her baseline SWLS score was 23/35. This individual's main goal was to regain the ability to run for one hour over-ground, as she had previously been able to do.

Participant Three

The third participant had been in a car accident almost five years prior to her participation in the study, and had sustained not only a TBI, but fractured fingers, spine, cheekbone, and ribs, and punctured a lung. She was kept in a medically-induced coma for two weeks at the acute care hospital, and later was admitted to a subacute rehabilitation setting for two months. At discharge she was able to walk with supervision, and she attended outpatient physical therapy for several months. She returned to college the following Fall. She stated she had been recently going to the gym two hours three times weekly, but fatigue had stopped her from doing so lately.

This individual was an athlete in high school and had bilateral ankle fractures, a fibular fracture, and ankle sprains in the past as a result of her participation in soccer. She also experienced frequent migraines and had lost sixteen pounds since the accident, which she attributed to loss of appetite. Other significant PMH included exercise-induced abdominal and calf cramping, which was not new after the accident, but was more severe. At baseline, she worked part-time and attended college full-time. She was independent with all ADLs and IADLs, including driving, transfers, stairs, and community ambulation without need for assistive devices.

Passive range of motion and MMT measurements were WNL throughout. Superficial, deep, and combined cortical sensation was found to be intact. Cranial nerve testing was WNL except she demonstrated slight decrease in eye coordination. Tone was WNL throughout bilateral upper and lower extremities, and no observable abnormal synergistic patterns were noted. Hyporeflexia was noted at the left bracheoradialis and achilles tendons, and decreased coordination was noted throughout the left upper and lower extremities. See Table 9 for strength and Table 10 for coordination testing details.

She had mildly decreased static balance in the left lower extremity as demonstrated by one-legged-stance testing. She was able to maintain the position for ten seconds on each side, but showed more postural sway when standing on the left foot. Sitting balance was WNL. She had no apparent gait deviations while walking, and was able to run independently at baseline. She did display mild foot drop, decreased weight-bearing on the left, and decreased left elbow movement while running at the initial evaluation. Her HiMAT score at baseline was 31/52.

Prior to her injury, this individual was a competitive soccer player and runner. She has not been able to return to her regular sporting activities since the accident, other than limited horseback riding. This participant’s goals included getting back in-shape, being able to run longer distances, improving her form during horseback riding, and returning to playing soccer at a higher level. She was concerned that her balance limited her ability to run, stating that she could only run on the treadmill for five minutes while holding on with both hands. Her initial SWLS score was 20/35.

Participant Four

The fourth participant experienced a TBI as a result of a car accident, about sixteen years prior to this study. She was in a coma for three months. After one month in acute care, she was transferred to a rehabilitation hospital and was discharged three months later. She continued outpatient physical therapy, occupational therapy, and speech therapy for another three months, and then continued to participate in all three of these at school until she graduated. She participated in weight training at home, as well as Pilates, twice weekly.

Significant PMH included congenital heart valve pathology, pneumothorax, scar tissue removal surgery, appendectomy/cholescystectomy, and three lumpectomies. Additional significant history included right middle ear surgery and revision, both of which occurred within the last few years. This individual mentioned her last seizure was over twelve years ago, but she still occasionally experiences an aura sensation with numbness in her right arm, which she stated she ignores.

She was independent with all ADLs and IADLs at baseline, including driving, and was employed full-time. She was also independent with transfers, stairs, and community ambulation without a device. It was noted by observation that she had some difficulty with motor control and planning, especially with complex or fast-paced tasks.

This individual's PROM was WNL throughout her upper and lower extremities. Her left upper extremity was noted to be 4+/5 and her left lower extremity was noted to be 5-/5, except for the ankle, which was 4+/5. All other strength measurements were WNL. See Table 11 and Table 12 for details of strength testing.

Sensation testing revealed decreased stereognosis and graphesthesia in her right upper extremity, and she noted paresthesias in her right hand. All other superficial, deep, and combined cortical processes were intact. Cranial nerve testing was intact except she demonstrated dysarthria and decreased hearing in her right ear. Hypotonicity was noted throughout her left lower extremity. No abnormal synergy patterns were apparent. Hyperreflexia was noted at the left biceps and brachioradialis tendons. Dysmetria and dysdiadokokinesia throughout her left upper and lower extremities was apparent during coordination testing. See Table 13 for details of coordination testing.

She was able to maintain one-legged stance for eighteen seconds on the left as compared to thirty seconds on the right. Static and dynamic sitting balance was WNL. No gait deviations were noted during walking. She was able to run at least 40 feet independently during the initial evaluation, although noticeable gait deviations were apparent. Her initial HiMAT score was 28/52.

This participant's baseline SWLS score was 9/35. Her goals were to increase cardiovascular endurance and to have a more normal walking and running pattern. She was interested in improving her agility in order to play tennis more skillfully. She stated she currently avoided running on the road because she felt self-conscious.

Participant Five

The fifth participant's TBI was caused by a fall with secondary complications, less than a year before participation in this study. She required surgery, and did not fully emerge from her coma until about four months after her injury. She remained in acute care for over a month and was admitted to a rehabilitation facility for 6 months, requiring two additional acute admissions due to complications. She was discharged to her own home with twenty-four hour care, and has been receiving outpatient physical therapy since her discharge.

Significant PMH included Graves disease, seizures, circulation problems, and a distant history of an ankle and collar bone fracture. At baseline, this participant had impaired short-term and long-term memory, which significantly affected her function. She was noted to have difficulty concentrating. Her hearing and speech were normal.

At baseline, she was able to eat independently, but required supervision for all transfers, stairs, ambulation without an assistive device, as well as to dress, and perform other ADLs and IADLs. She was unable to drive, and was not employed.

Bradykinesia and the appearance of slowed processing were observed throughout the baseline evaluation. Upon functional mobility testing, she was independent with bed mobility and sit-stand transfers, but required distant supervision for ambulation outdoors, and supervision while ascending or descending stairs.

This individual's PROM testing revealed limitations in shoulder flexion and abduction, hip abduction, and ankle dorsiflexion, bilaterally. See Table 14 for more details. Manual muscle testing revealed impaired strength throughout bilateral upper extremities and lower extremities. See Tables 15-17 for details of strength testing.

Sensation testing revealed intact superficial, deep, and combined cortical processes. Cranial nerve testing was intact throughout all tests performed. A slight increase in tone was noted in bilateral shoulder flexors, abductors, and internal rotators; elbow and wrist flexors; hip extensors, adductors, and internal rotators; knee extensors; and ankle plantar flexors. Bilateral biceps, brachioradialis, patellar, and left achilles deep tendon reflexes were noted to be hyperreflexic. Coordination was noted to be minimally impaired throughout bilateral upper and lower extremities. See Table 18 for details of coordination testing. This participant was unable to maintain one-legged stance on the left, but was able to do so for 5 seconds on the right. She was able to maintain tandem stance for 10 seconds. Sitting static balance was WNL, however dynamic sitting balance was minimally impaired. She was unable to run during the initial evaluation. Her initial HiMAT score was 10/52.

Prior to her injury, this individual had been very active, participating in many types of aerobic activities for up to two hours per day. This participant's baseline SWLS score was 12/35. Her goals were to walk and run normally, but she did not specify a running distance or time that she wished to achieve.

All of the participants in this study fell into The Guide to Physical Therapist Practice's Preferred Practice Pattern 5D: Impaired Motor Function and Sensory Integrity Associated with Non-progressive Disorders of the CNS- Acquired in Adolescence or Adulthood.[51]

Design

Originally this study was a modified control-group experimental design, but too few participants were recruited within the allotted time frame and only one participant was randomly assigned to under-water treadmill training. As a result, this paper will describe a within subject design using only those participants receiving BWSTT. The independent variable for the study was an intense exercise program broken into three phases. The first phase focused on strength training (six weeks), the second phase focused on BWSTT (six weeks), and the last on over-ground running and sport-specific activities (three weeks). Dependent variables included the HiMAT,[52] lower extremity muscle strength, maximum running distance, running speed, quality of running, and quality of life.

Sample Selection

A combination of non-probability sample methods including convenience and snowball sampling was used. Some recruitment techniques included posting fliers, giving in-service presentations, and word-of-mouth invitations through a local rehabilitation center. Since the population of interest included only high-level individuals with TBI who had an interest in running again, snowball sampling provided the best way to recruit enough participants from a limited population in an area close enough for them to be able to travel to campus twice weekly without undue inconvenience. Data from a total of five participants was collected. Written informed consent was obtained from all participants of legal age. The first participant verbally assented, while his parents gave written informed consent. The signed letter confirmed risks and benefits of participating in the study, as well as confirmation that confidentiality would be maintained according to the Health Insurance Portability and Accountability Act standards. Human subject approval was given by The Sage Colleges Institutional Review Board.

Inclusion/Exclusion Criteria

To be included in the study each participant must have been able to walk independently without an assistive device for 200 feet, climb a flight of stairs, have strength deficits on one side of their body greater than the other, have experienced a TBI at least 6 months prior, as well as having been cleared by a physician to run. Participants may not have had a history of myocardial infarction, resting blood pressure 200/110 or higher, resting heart rate less than 50 or more than 110, uncontrolled metabolic conditions, a history of uncontrolled seizures, additional neurological diagnoses, current orthopedic conditions that would affect ability to run, or be pregnant or expecting to become pregnant. See Appendix A for the screening instrument used to determine whether interested parties met the criteria for the study.

Instrumentation

Outcome measures used for this study included high level mobility function, as measured by the HiMAT;[52] lower extremity muscle strength, as measured by HHD; maximum running distance, as measured by laps around a marked 50 foot by 64 foot indoor course; running speed as measured by a 10 meter run; quality of running; and quality of life, as measured by the SWLS.[53] Outcome measures were taken at baseline and at the completion of each phase of the study, as well as at week three of phase one to help guide treatment. Outcome measures were taken by a blinded physical therapist with 25 years of experience, who had been trained by the principal investigator. All outcome measures were performed in the same order with each participant to ensure standardization, and each individual measure was performed within the same two rooms in order to minimize the effect of environmental factors on the results.

The HiMAT [52] is a thirteen-item tool used to assess high level balance and mobility function. Assessment items include walking forward, walking backward, walking on toes, walking over an obstacle, running, skipping, hopping forward, bounding on both the affected and less-affected leg, and ascending and descending stairs. HiMAT[52] scores were then converted with the use of a table, and the individual was placed into a category between zero and five, with a higher number indicating a higher level of function. The participant received a score of zero on any item that they were unable to initiate. Appendix B includes the HiMAT[52] form.

Inter-rater and test-retest reliability of the HiMAT[52] are high (ICC= 0.99), as is internal consistency (0.97- Cronbachs alpha). Concurrent validity with the motor component of the FIM and the RMA was 0.53 and 0.87, respectively. The authors concluded that ceiling effects of the FIM and RMA accounted for much of the disparity. The HiMAT was also found to be more responsive to change than the other two tools.[54]

Lower extremity muscle strength was measured using HHD on bilateral hip flexors, abductors and extensors; ankle dorsiflexors and plantar flexors; and knee flexors and extensors in order to determine if strength changes occurred over the duration of the study. Dynamometry measures the force produced during an isometric contraction in kilograms. Participants were instructed to attempt to move the joint indicated with each muscle group of interest, while they pushed against the therapist's resistance to create an isometric contraction. Two trials were taken for each measurement and the results were averaged. The procedure was based on an article by Andrews [55] with some modifications. Modifications were implemented due to less than satisfactory reliability values (<0.70) for knee and hip extension in a pilot case study,[31] as well as the possibility of the participant overpowering the tester. [56] Modifications included change of positions, the addition of an aid who would stabilize each individual at predetermined sites, as well as the use of a custom made chair platform and gait belts for knee flexion and extension testing. See Appendix C for the HHD protocol.

A pilot study was performed by the outcome assessor in ten healthy individuals to assess intraclass reliability. Intrarater reliability was high (ICC> 0.85) for all muscles. According to the literature, intersession reliability of HHD for healthy young people is between 0.62 and 0.92.[56-58] Test-retest reliability was found to be between 0.55 and 0.99 for adults and children with neurological diagnoses.[59-62] Although one study showed variable results, we believe the overall reliability, as shown by the body of current literature, is strong for HHD, and provides a more objective and sensitive tool to measure changes in strength with this population than manual muscle testing could provide.

Hand held dynamometry testing of knee extension was found to be valid when correlated (r = 0.71-0.86) to the TUG, which supports that it is well correlated to functional status.[63]

Additionally, a review article of nineteen studies found minimal differences between HHD and isokinetic muscle strength testing as the reference standard. HHD is also portable, easy to use, and less time consuming than isokinetic testing.[64]

Maximum running distance was measured on a marked 50 feet by 64 feet course. Laps were recorded and converted to overall distance covered. Each participant was instructed to run at a pace they believed they could maintain for a period of time, since this trial was to measure distance, not speed. Reasons for stopping included muscle fatigue, shortness of breath, and orthopedic pain. No research was found about reliability or validity for measuring running distance but timed walking distance has been shown to have high test-retest reliability in people with neurological impairments (r=0.95-0.98).[65]

Maximum running speed was assessed using a timed 20 meter sprint using a stopwatch to time the middle 10 meters of the test. Standing at the starting point, the participant was instructed to run as fast as possible when the therapist said “Go”. The time of the middle 10 meters was recorded and converted to meters per second. Reliability of the 50 yard dash was high (ICC=0.98) in a study that looked at people ages 9-17 with TBI.[66] The length of the sprint was cut down for the present study to accommodate for the abilities of the participants.

Quality of running was determined by videotape analysis in order to gain an objective picture of the participants’ running deviations. The participants were video recorded during the above maximal running speed test using software from Sports Motion, Inc.[67] It allowed for multi-angle recording (front, back, and side views) with memory for future analysis, instant replay, as well as freeze frame and slow motion features. Sports Motion Markers[67] were placed on bilateral lower extremities on bony landmarks (ASIS, patella, talus, greater trochanter, fibular head, lateral malleolus, popliteal fossa, and achilles tendon) to visually aid the reviewers.

The Frear-Moriello Running Analysis Form was used to make the gait analysis process consistent. Three licensed physical therapists independently viewed the videos from the initial evaluation and at discharge. One therapist had 13 years of experience, was a board certified neurology clinical specialist, and has worked with people with neurological diagnoses for 10 years. The second therapist had 35 years of experience with a clinical expertise in outpatient orthopedics. The third therapist had over 25 years of experience in a variety of clinical settings. The forms from each observer were combined for the final results. It was considered a change when two out of three therapists noticed the same running characteristics. See Appendix D for the Running Analysis Form and its interpretation.

The SWLS was administered to measure quality of life. This tool was added to the outcome measures performed in order to get a subjective angle of how the interventions were affecting each participant's quality of life. This easy to use, quick, five item questionnaire was developed by Diener.[53] Participants rated each item on the scale from 1-7, representing a continuum from strong agreement to strong disagreement. The instrument was scored by simply adding the total of the numbers for each item. Point scores between 5 and 9 represented that the individual was extremely dissatisfied with their life, while point scores between 31 and 35 represented that the individual was extremely satisfied with their life. See Appendix E for a copy of the form. The SWLS demonstrates high test-retest reliability (0.82) as well as moderate concurrent validity noted with correlations between this and other subjective measures of quality of life and subjective well-being (.32-.75).[53]

Convergent validity was confirmed by the finding that depression was a negatively correlated factor (r = -0.44), and that social support was a positively correlated factor (r = 0.39). Internal consistency was calculated to be 0.92, using Cronbach’s alpha. The authors also performed an analysis of variance including age and gender to determine whether these would present as confounding factors. Results showed that no change in scores could be attributed to the influence of age, gender, or a combination of the two.[68] This is important to note considering the fact that four out of six participants in our study were female, and all of our participants were young adults (between high school and early forties).

Protocol

Participants were trained two times each week with sessions lasing approximately one hour and fifteen minutes. Training sessions were conducted by one of three licensed physical therapists and one of seven physical therapy students. The principle investigator has practiced for 23 years, is a board certified geriatric clinical specialist, and has worked in the neurological population for 23 years. The second therapist has practiced for 12 years, 10 years within the neurological population and is a board certified neurological clinical specialist. The third therapist had two years of experience in the orthopedic setting and was a certified strength and conditioning specialist. There were three phases in the training protocol, which lasted a total of 15 weeks. The first session served as the initial evaluation for each participant. A written protocol was followed for each of the phases as outlined below.

Phase I consisted of six weeks of strength, agility, and balance training. The purpose of this phase was to prepare each participant for the demands of running in phase II. Each session consisted of approximately five minutes of aerobic warm up (usually walking or jogging) followed by five minutes of dynamic stretching. Twenty minutes of each session involved static and dynamic balance training with progression from double limb to single limb activities and dual task training on a variety of surfaces primarily from a pre-generated list of exercises. Participants then performed agility and/or plyometric training for twenty minutes, and strengthening exercises for the core and lower extremities for fifteen minutes of each session. For each category, participants progressed at his or her own pace, as deemed safe by the treating therapist. There was a five minute cool down at the end of the session involving the same type of aerobic exercise as the warm up followed by passive stretching to the main muscle groups used for running. About ten minutes of each session was allotted for rest breaks. Participants were permitted to stand, walk, or sit if necessary during these rest breaks.[69,70]

During phase II, participants performed BWSTT for a period of six weeks. Equipment included the LiteGait I-350 and TRUE s.o.f.t. treadmill # 725. Two protocols were set up for phase II, one for speed and one for distance. At each session, participants completed one trial of the distance protocol and two trials of the speed protocol. The order of the trials was predetermined to be distance/speed/speed for the first session of the week and speed/speed/distance for the second session. Vitals were taken prior, during, and after exercise. The Borg rate of perceived exertion (RPE) scale was used during interventions to determine that proper exertion level was not exceeded. The Borg RPE scale uses numbers 6 through 20 for participants to quantify as well as qualify how hard they feel they are working. The number 6 correlates with ‘no exertion’ while a 20 correlates with ‘maximum exertion’. See Appendix F for the RPE scale. A poster of the number scale with associated phrases was hung within the participant’s view in order to make it easy for them to report their RPE during treadmill training. All participants warmed up and cooled down for five minutes at their preferred walking speed. Each speed trial lasted to the participant’s tolerance or four minutes maximum, including a two-minute warm up, two-minute speed trial, and one-minute cool down. On the first day, each participant began at 30% unweighing and was instructed to run at the fastest speed they could tolerate for 2 minutes. This is the speed at which the participant demonstrated correct body mechanics as determined by the physical therapist and had fewer than ten scuffs (when the foot hits the treadmill during swing advancement). This speed was used as the participant's starting velocity during the first speed trial.

Once the participant was able to run at the maximum speed for two consecutive four-minute trials, BWS was decreased in increments of ten percent. The above process was repeated until the participant reached zero percent unweighing at which point the speed increased by 0.2mph at each session. If the participant was not able to run at the increased speed without proper mechanics and fewer than ten scuffs, the unweighing was increased by five to ten percent as needed.

To work on running distance, participants ran at a speed where they rated themselves as an 11 or 12 on the RPE scale during the first three weeks and as a 13 during the last 3 weeks. The amount of BWS for the distance trials was the same as that used for the speed trial warm up during that session. Participants ran at the determined speed as long as they could for up to 30 minutes. If the participant showed any signs of struggling (more than ten scuffs, decreased biomechanics or stumbling), exceeded ACSM guidelines for vital signs, or if verbalized the desire to stop, the trial was terminated. After the BWSTT each participant practiced overground running for two five meter runs.

The final phase lasted three weeks and incorporated over ground running, strengthening, and sport specific activities. Approximately 15 minutes was dedicated to strengthening muscles that were found to be weak upon re-evaluation. Between 30 and 45 minutes was spent on overground running including speed and distance trials and 15 minutes were spent practicing a specific sport of interest or associated drills. The over ground running followed the same protocol as phase II, alternating distance/speed/speed and speed/speed/distance running trials between sessions. In this phase however, the speed trials were performed by the participant running the length of the gym. Sports of interest with this group of individuals included baseball, basketball, soccer, and tennis. Warm-up, cool-down, and stretching were also stressed during this phase. Both static and dynamic stretching techniques were used at the therapist's discretion and according to the individual's needs.

Data Collection Procedures

During each evaluation, all outcome measures were performed and recorded. Data were collected using a flow-chart during each exercise session. Vitals, distance and speed of running, parameters of any training equipment, as well as a list of all therapeutic exercise and dynamic activities done throughout each session were recorded. A SOAP note for each session was also included in order to obtain subjective and objective feedback, report the patient's response to each session, plan for future sessions, and make note of any unique considerations.

Data Analysis

Data was analyzed with the use of SPSS 19.0 software. Wilcoxon Signed Rank Tests were used to find the effect of treatment on running speed, distance, and HiMAT scores from pre-test to post-test. The p value was set as 0.05. Nonparametric tests were used because of the small sample size of 5 participants. The use of Bonferroni corrections to counteract the problem of multiple comparisons was considered, but ultimately not used due to the small sample size and effect on power. Strength was assessed by determining the percent change from baseline to the final evaluation in bilateral lower extremity strength for each participant. Real changes were identified as those greater than + or - 20%. Running quality was analyzed by three licensed physical therapists. Reviewers watched the videos of each participant running at pre and post testing and recorded qualitative data on the Frear-Moriello Gait Analysis form during each phase of gait. Due to the fact that not all participants completed Phase III of the protocol, the last data point available for these individuals was included in the analysis. Satisfaction with Life Scale scores were totaled and compared for each participant for pre-test to post-test.

RESULTS

The study participants were 80% female and 20% male with a mean age of 28 years. The average inpatient stay was six months, while average number of years post-injury was six years. Detailed baseline characteristics for all participants are presented in Table 19 and Table 20.

Although five individuals began participation in this study, only two individuals completed the full 15 week protocol. One individual completed 10 weeks of the protocol before moving to a different state where she was unable to fulfill the program requirements. The second individual completed 9 weeks of the program before she was put on hold from participation in the study due to increasing fatigue and seizures due to mild kidney failure. A third individual was hospitalized due to pulmonary emboli.

Results of Wilcoxen Signed Rank testing revealed significant improvements from pre-test to post-test in running speed ($p = 0.04$) and HiMAT scores ($p = 0.04$), but not running distance ($p = 0.14$). Table 21 depicts the results of Wilcoxen Signed Rank testing. Although there were no significant changes identified in running distance from pre-test to post-test, improvements in individual performances were identified. Percent changes in individual running distance ranged from -4% to 4043% from pre-test to post-test as depicted in Figure 1. Improvements in overground running speed from pre-test to post-test ranged from 3% to 35% and are provided in Figure 2. Figure 3 demonstrates improvements in HiMAT scores from baseline to post intervention, ranging from 4% to 200%. The mean change in HiMAT scores from pre-test increased by 8 points upon post-test assessment.

Throughout therapeutic exercise interventions, participants demonstrated a generally rapid increase in heart rate response to aerobic activity that returned to baseline levels during periods of rest. The heart rate for one participant increased from 84 at rest to 172 bpm following a distance running trial, demonstrating this rapid increase. Overall, blood pressure measurements were observed to be on the low end of normal, with one individual's blood pressure measured as 78/56 at rest. The blood pressure responses of all participants to exercise fell within ACSM guidelines and did not exceed a change of 20 mmHg with activity. Participants also demonstrated a rapid recovery of blood pressure and heart rate measurements to baseline levels following cessation of exercise.

Changes in lower extremity strength from pre-test to post-test varied by participant, as reported in Table 22. Table 22 outlines the trends in strength gains and declines of greater than 20% from baseline to post-intervention. There were consistent increases in strength among the participants in ankle dorsiflexion, plantarflexion, and hip extension and consistent decreases in hip flexion and knee extension. There were inconsistencies among the participants in changes in hip abduction as seen in Table 22.

Participant one demonstrated changes in quality of running from pre-test to post-test including the following: a more symmetrical gait with regard to weight-bearing and stance time, improved hip extension during initial swing, change in initial contact point of the impaired extremity from forefoot to midfoot, and improved push off during toe off.

Throughout the running stride cycle, participant two showed more equal weight-bearing and stride length, improved linearity of gait pattern with better balance and control of weightshifting, improved double float, increased trunk rotation during loading response, improvement in hip extension during toe off, increased hip and knee flexion during initial swing, increased knee flexion during midswing, better knee extension, better knee stability during midstance, improved plantar flexion, and improved arm swing.

Participant three was observed to have increased speed, less aberration from a linear gait path, decreased excess hip external rotation throughout swing phase, decrease in the degree of lateral heel whip during swing phase, and improved symmetry of upper extremity position and swing. Participant four also showed increased speed and a more symmetrical gait pattern with less aberration from a linear path, as well as improved trunk rotation throughout the gait cycle, less hip internal rotation during swing phase, and improved upper extremity symmetry and mechanics. Participant five was closer to double float, demonstrating ability to run, which she was unable to achieve at pre-test. Increased speed at post-test was observationally noted, as well as improvements in amplitude of arm swing bilaterally.

The SWLS was completed by only two participants at both pre-test and post-test. There were no measurable changes in cumulative scores on the SWLS from the initial evaluation to the post-intervention assessment. The total scores for one participant remained the same, however the cumulative scores for the second participant decreased. Overall, the responses on the SWLS's individual items varied considerably. The final item on this questionnaire, "If I could live my life over, I would change almost nothing," was initially rated as a 2 ("Disagree") and increased in satisfaction to a 7 ("Strongly agree") by one of the participants. Another participant reported a decrease in satisfaction with life as indicated by rating the item "So far I have gotten the important things I want in life," as a 5 ("Slightly agree") at pre-test and a 1 ("Strongly disagree") at post-test.

DISCUSSION

The purpose of this study was to identify and assess the differences in functional mobility, lower extremity strength, running distance, running speed, running quality, and quality of following an intensive endurance, strengthening, and flexibility program paired with BWSTT in individuals with TBI. The unique protocol used throughout this pilot study yielded significant changes in running speed and HiMAT scores over a period of 15 weeks. Although participants were able to run overground a greater distance from pre-test to post-test individually, no statistically important changes were found in running distance over time. Changes in strength following the intervention period were inconsistent, but there was a trend in gains of greater than 20% in ankle dorsiflexion and plantarflexion, hip abduction, and hip extension strength. The changes in quality of gait found in our study included improvements in active range of motion, balance and control, symmetry of weight-bearing and movement patterns bilaterally, and reduced displacement from a linear path. Quality of life did not change significantly in the two participants who did complete the final survey, with some variation in both positive and negative responses from pre-test to post-test.

The current study yielded an average of 22.7% improvement in overground running speed that may be attributed to the intensity and specificity of training. The training regime included participation in speed trials during each session throughout phases II and III, as well as an individualized preparation phase designed to maximize agility, proprioception, balance, and single and double-leg dynamic stability. Since agility training often includes repeated eccentric contractions and changes in direction, these activities were thought to have translated to increased ability to produce eccentric forces required to run, especially at high velocities.

This increase in running speed is consistent with the improvements noted in Miller,[71] but is not as significant the results of the Moriello.[31] Miller[71] showed a 12.4% increase (from 3.39-3.81) in sprint speed after a similar program post-stroke. Moriello[31] produced a 591% gain in running speed utilizing a similar program with an individual diagnosed with chronic TBI. The degree of improvement between the current study and the Moriello[31] study may be related to the intensity of the program, length of the program, participants' baseline characteristics, range in severity of chronic TBI-related impairments, time status post injury, or age.

Participants demonstrated improvements in HiMAT scores from pre-test to post-test with an average increase of 8 points. According to the literature, the MDC value for this assessment tool is 4 points[52], providing evidence beyond measurement error. These outcomes are similar to those of other studies using the HiMAT as an assessment tool for individuals with TBI participating in an exercise program. Williams[43] found an average 9 point improvement in HiMAT scores in individuals with TBI following a three month dynamic strengthening and agility program. A second study investigated the effects of a six month high-level mobility and overground running program on a 52 year old male with hemiplegia and 24 year old male with ataxia as a result of a TBI. These individuals demonstrated improvements in HiMAT scores of 11 and 40, respectively.[72] Those scores obtained from the literature were fairly comparable to those found in our study.

Current literature supports the theory that the adult brain is capable of plastic changes both directly after and many years post injury. This re-organization, re-assignment, and new growth of neurons was previously believed to occur exclusively during developmental stages.[73-75] Donald Hebb, who developed this idea, noted that increased load placed on a given neural connection made it stronger, while those that were not frequently used became weaker.[76]

Therefore, we argue that successful rehabilitation of those with non-progressive neurological disorders requires intense and repetitive training to elicit neuroplastic changes.

In addition, acute aerobic exercise has been found to temporarily increase brain-derived neurotrophic factor in animals and athletes with chronic spinal cord injury.[77,78] Brain-derived neurotrophic factor is a chemical that promotes neuroplasticity in the central nervous system.[73] Thus, promoting an active lifestyle through exercise may aid in continued recovery of function after the acute recovery period is over.

The fact that there were no significant changes in running distance from pre-test to post-test is not consistent with the literature. The literature reports improvements in running distance in individuals with TBI and stroke following an intense agility program and a task specific training regime, respectively.[31,71] Ultimately, participants in both of these studies were able to run a greater distance for a longer amount of time when compared to baseline.

Although improvements in running and walking distance were seen in other studies, the fact that running distance did not significantly improve in this study may be due to multiple factors. This program was a pilot study, therefore a small number of individuals were recruited to participate in the intervention program. We believe that the primary reason for non-significant changes in running distance can be attributed to this small sample size. Additionally, one of the participants demonstrated a lack of motivation in the final evaluation and left early. This participant admitted that she could have run further but needed to leave for reasons unrelated to this study. Another factor that may have played a role in these findings include the inefficient running pattern that many individuals with TBI employ, due to factors such as hemiparesis, decreased sensory perception, and tonal influences. It is possible that these abnormal mechanics do not allow for maintenance of such a high intensity over time, depending on the level of impairment.

Although all of these factors may have contributed to a lack of significant changes in pre-test to post-test running distance, the majority of participants demonstrated personal gains in running distance, ranging from -4% to 4034%. Additionally, individuals participating in the study were able to meet many of their personal goals as provided in Table 20. One individual participating in the study was able to run a 5K race in under 28 minutes, while another was able to run 200 feet and participate in baseball in gym class.

Lower extremity strength changes were inconsistent among all of the participants from pre-test to post-test. The muscles that appeared to show the most consistent improvements throughout the intervention period included the hip extensors, hip abductors, ankle plantarflexors, and ankle dorsiflexors. The extensors and the plantarflexors are muscles that are characteristically utilized during running to propel the body forward overground, and the abductors are used to stabilize the position of the pelvis relative to the running surface. These improvements were anticipated because participants performed a series of high-intensity closed chain activities that required individuals to use the large extensor muscles for lower extremity power exercises, as well as the use of the hip abductors for stability, especially in single-leg stance positions. Moriello[31] also identified variable changes in lower extremity strength in a 17 year old male with a TBI who completed a similar three-phase training program. This participant demonstrated improvements in hip extensors, knee extensors, ankle plantarflexors, and ankle dorsiflexors following the intervention program. The authors also attributed these gains to a focus on closed chain activities that targeted extensor muscles that were necessary for running.

Miller[71] found at least a 20% improvement in bilateral hip flexors, left hip abductors, bilateral hip extensors, left ankle plantar flexors, bilateral ankle dorsiflexors, and bilateral ankle evertors in a 38 year old male following a stroke. These findings are also similar to those in the current study.

Inconsistencies in the current strength findings may be attributed to various physical and psychological factors of the participants. One individual reported feelings of fatigue during phase II of the protocol which was found to be the result of mild kidney failure associated with her medication regimen. This may have affected her strength during re-assessment, when almost all the strength values were found to have decreased.

Many of our participants demonstrated improvements of gait quality, the most common improvements noted were symmetry and mechanics of upper extremity movement, symmetry of weight bearing, stance time, and stride length, and decreased aberration from a linear running path. These occurred in at least three out of five participants. At least two out of five participants showed improvements in double float, trunk rotation, hip extension, and hip rotational positioning during swing phase. These results can be compared to the research of Williams[72] who demonstrated improvements in walking quality after a similar twenty-four week program.

Improvements in running quality contributed to the efficiency of each participant's running pattern, and we believe this was related to the significant improvements noted in running speed and high level mobility. The goal of our individualized strength, balance, agility, and sport specific overground training was to minimize the effort required to run by targeting specific areas of impairment, encouraging a more symmetrical and stable gait pattern, and enabling each individual to participate in their sport or activity of interest with less difficulty.

Although the SWLS did not reveal significant objective improvements in quality of life, anecdotal information provided by participants and their families helped to provide evidence that participants lives were positively affected. All except one participant received a six month follow up phone call from the principal investigator of this study. Responses varied among participants, however each discussion revealed information regarding how the study has changed aspects of their lives. The mother of one participant reported he was less fearful about ambulation, was able to transfer independently off of the floor, and could run around the bases in gym class. His school physical therapist stated that prior to the study she was able to hear him walking down the hallway, however following the protocol his footsteps were less audible. Another participant reported running every day and had participated in several road races since the completion of the study, including two four-mile races. Her mother also reported that she feels the running helps her daughter's psychological status and gives her purpose in life. A third participant reported working with a personal trainer and physical therapist, playing tennis and squash, and going to Pilates after discharge from the program. A fourth participant stated she was able to run for half an hour on the beach and currently walks five miles per day, since she prefers walking over running.

It is interesting to note that the participant's families expressed satisfaction with improvements in lower level skills following discharge. These subjective acknowledgements agree with the literature in suggesting that individuals who are willing to undergo intensive rehabilitation are likely to demonstrate improvements in lower level tasks, such as walking quality, in addition to high-level tasks that were the focus of the intervention.[72]

Traumatic brain injury is a diagnosis that the public frequently perceives as a permanent and disabling injury that renders the person unable to return to high-level activities. Current rehabilitation programs for TBI are centered on regaining basic mobility and independence, but overlook the possibility of resuming safe participation in sports and recreational activities. Third party payers are reluctant to compensate clinicians for higher level skills training in individuals with neurological diagnoses because it surpasses the necessary requirements for independent function, and is therefore not "cost effective." The lack of availability and coverage of programs that provide intense exercise training has fostered the misconception that individuals with TBI will never be able to participate in previously enjoyed recreational or sports activities. The program developed in this study can combat these negative ideas by promoting higher levels of function, increasing participation in recreational activities and community events, and improving overall quality of life. These outcomes may ultimately decrease the cost of healthcare in the future by minimizing doctors' visits for psychosocial concerns and comorbidities associated with inactivity over the lifetime. This study is one of the first of its kind to investigate the effects of intense sport-specific training and body-weight supported running on running speed, distance, and quality, high-level mobility, and quality of life in individuals with TBI.

Furthermore, it is shown in the literature that those with TBI who are sedentary tend to be more deconditioned than their brain injury free counterparts in society. It should be duly noted, that 27% of the population of those with TBI in the USA do not exercise even weekly, which is far below the ACSM's recommended level of activity for any healthy adult.[19] Consistent participation in exercise is known to play a major role in prevention of cardiovascular disease, management of mood disorders, and in maintaining health and functional strength of the musculoskeletal system, including prevention of osteoporosis and many other conditions caused by disuse of the bodies' functional abilities. Involving people with TBI in exercise and higher level activities could improve their quality of life and overall health.

The sample in the present study generally developed a high heart rate response to exercise while blood pressure response appeared to remain within normal limits. Two of our participants did have very low resting systolic blood pressure (less than 90 mmHg), but this was not a major concern because they both had history of low blood pressure dating before their injury. Many of those with acute TBI have autonomic dysfunction that alters normal control of resting vitals as well as response to exercise. The literature supports the idea that those with hypotension after acute TBI tend to have poorer outcomes,[79-81] however there was no information found in the literature regarding chronic cardiovascular changes in the TBI population. The abnormal heart rate response to exercise could have been due to autonomic dysfunction or generalized deconditioning from lack of exercise since the time of injury.

The available literature suggests that although autonomic dysfunction is often present in individuals with TBI, it may resolve during the subacute phase.[82] It has also been noted that those with chronic TBI show a consistent and reliable cardiorespiratory response to exercise,[83,84] but are significantly more deconditioned than a matched group of sedentary people without disabilities.[85] Although we followed the ACSM's guidelines for exercise training intensity, in future studies, it would be appropriate to use the Karvonan formula to determine an appropriate heart rate range. Since all of the participants in the present study were in the subacute or chronic phases it is likely that any abnormal vital response was due to deconditioning rather than autonomic dysfunction.

Monitoring vitals/symptoms and close communication with the patient's primary care doctor regarding any changes is essential, given the fact that many of those with TBI will require long-term use of medications that may have side effects. During the present study, changes in vital signs and symptoms of two of our participants were noted. One participant reported fatigue and had decreased muscle strength while the other reported dizziness with pulse oximetry levels that dropped with exercise. One was subsequently diagnosed with kidney failure related to medications, and another with multiple pulmonary emboli. This is an example of why it is important, in any rehabilitation setting, to keep a record of baseline and follow up treatment vital signs.

Due to residual impairments including strength, sensation, joint position sense, coordination, asymmetry, and weakness that may be experienced by those with chronic TBI, this population may be at an increased risk for developing overuse injuries. A study looking at long-term musculoskeletal complaints after TBI found that 79% of people who sustained a moderate-to-severe TBI, 15 or more years prior, reported some form of musculoskeletal issue.[86] No literature was found related to the risk of overuse injuries in the athletic population with chronic TBI or spinal cord injury, however in the healthy population, research indicates that risk of developing an overuse injury during running is a multi-factorial concern that single-factor analysis cannot properly assess.[87,88] Because anatomy, running style, and training method are not homogenous across individuals, it is difficult to pinpoint the factors that put an individual at a greater risk for overuse injury, without acknowledging the effect of confounding variables.

Development of overuse injuries in those with abnormal joint mechanics and patterns of motion are thought to occur over time by repetitive application of forces that the tissue is not designed to conform to. Improper training or running with faulty or anatomically-driven abnormal biomechanics does appear to cause increased frequency of overuse injury. We believe that individuals who have asymmetrical and abnormal joint mechanics due to chronic impairments as a result of TBI will have a greater risk of overuse injury within a given distance of running than someone without these impairments. According to the literature, ankle range of motion, ankle strength,[89] rear-foot positioning during heel strike,[90] severe or asymmetrical Q-angle,[91] and severe pronation[88] all appear to play a role in the risk of developing overuse injuries.

This projected elevated risk for overuse injuries is one reason why the protocol was developed in three phases, providing individualized strength, agility, dynamic stability, and balance training for six weeks prior to introducing the body to the demands of running. The un-weighting effect of the body-weight support system during phase II was intended to be a safe way to gradually introduce the high musculoskeletal loads and eccentric forces demanded of the body during running overground.

Even though the protocol was designed to prepare participants for running and to avoid musculoskeletal injury, some participants still developed transient pain. One participant reported right medial knee pain during phase two of the protocol that lasted about two weeks. Another participant reported two instances of left hip soreness; once during phase I and once during phase II, each lasting about one week. The same participant reported generalized, transient bilateral ankle pain during phase III, as well as some skin irritation from the groin strap used during BWSTT. A third participant had a wrist sprain from a fall during the first two weeks of the protocol, as well as recurring left ankle pain during the beginning of the study, that resolved near the end. This participant also reported right ankle pain during the first two weeks of phase II.

Although there are positive and encouraging findings, this study has several limitations. The most significant limitations were the small sample size and lack of control group. Participating in this study involved a large time commitment and the ability to travel to the Sage Colleges twice each week for 15 weeks. Despite recruitment efforts in the area, it was difficult to find a large number of individuals to take part in the program who also met the inclusion criteria and wanted to return to running and sports. Recruitment may have been more successful in a larger city, or with coordination of the project through multiple PT graduate programs across a larger region. Although it was a small sample size, this was intended to be a pilot study so for that purpose the sample size was sufficient.

Along with a small sample size there were also participants that did not complete the full 15 week protocol. Participant three re-located before she was able to begin phase III of the protocol and participants four and five did not complete due to unrelated medical issues. However, these participants still demonstrated improvements and the results were statistically significant. We believe that completion of all phases of the protocol would have led to even greater outcomes.

There may be a limitation with the method used to assess strength. A study by Morris[62] suggests use of three trials of HHD; the first trial for familiarization and the second and third to be averaged to provide a typical measure of isometric muscle strength. However, we utilized two trials of HHD testing for each participant, and averaged the results, in order to get accurate measurements without fatigue.

The use of HHD to test muscle strength was effective for isolating specific muscle impairments, however in retrospect, we believe it would have been more appropriate to include a strength outcome measure that integrated closed chain, task specific items that require core stability and balance. Two examples that could have been used are the 5 repetition sit-stand test, which has been shown useful in the stroke population[92] or the standardized assessment outlined in the book *Movement: functional movement systems*.[93] Although isokinetic muscle strength testing is considered the gold standard, its use with those with neurological diagnosis may be limited by poor test-retest reliability.[94]

Long-term objective follow-up data that would have assessed the dependent variables' changes over time after completion of the protocol was not collected. However, as previously mentioned, follow-up interviews were performed by the principal investigator to determine whether the participants' satisfaction with their results had continued.

Subjective improvements in quality of life were noted by each participant or their family members, but this did not correlate with our findings when implementing the SWLS. We retrospectively noted that this tool focuses on attitudes toward life rather than the outward signs of improved quality of life, and one question focuses on whether or not the individual would want to change anything about their past. Given the history of TBI with our participants, we feel it may have been more appropriate to administer an outcome measure that is more specific to their diagnosis and goals.

Future Research

Since this was intended to be a pilot study, the authors would like to see additional research done with a larger sample size. It would be valuable to carry out a similar study with a control group using a different mode of body-weight support, such as underwater treadmill training. The addition of a control group without the use of body-weight support would also be useful to determine whether differences in outcomes would occur.

In this study, we required each participant be cleared to run by their physician, due to the potential for medical fragility and the possible effect of changes in medication. We would value future research that develops standardized criteria for return to sport after TBI[95] as well as guidelines for exercise in the population of those with chronic TBI. We believe the presence of parameters for safe return to high-level exercise would encourage a more active lifestyle in this population.

We also argue that since bounding, toe walking, retro-ambulation up stairs, and maintaining single leg stance are predictors of an individual's ability to run after TBI,[96] that any program focusing on high-level mobility training in this population should include task-specific strength, agility, and balance exercises, progressing from double to single-limb activities. We also propose the addition of walking gait analysis to the dependent variables in the future, since several of the participants and their families subjectively noted improvements in lower level functions after discharge. On the same note, it would be valuable to test whether walking distance also would have improved, using the six minute walk test, which has been validated in this population.[97] A study with a similar program reported significant gains in six minute walk test distances, as well as maximum distance ambulated in an individual with the same diagnosis.[35]

Due to the limitations of the SWLS, we suggest several alternative quality of life measurement tools that may be more appropriate. The literature indicates that The Craig Handicap Assessment and Reporting Technique (CHART), is valid "when measured against real world indicators of outcome from head injury,[98]" and it has good psychometric properties in those with spinal cord injury.[99] The Community Integration Questionnaire (CIQ) focuses on activities and community participation rather than attitudes. Although the psychometric properties of the CIQ and CHART are not ideal,[100-102] these tools are very specific to the population in question.[103] Another quality of life measure that covers broad categories of health-related aspects of QOL is The Duke Health Profile, which has good psychometric properties,[104] but is not disease-specific. A reliable and valid QOL tool which is specific to the population in question still needs to be developed.

Conclusions

There is limited literature regarding outcomes of running programs for individuals with TBI. However, the present study currently has the highest number of participants related to this subject. The results of this study add new information to the world of neurorehabilitation research about the potential for improvements in mobility, strength, and running distance, speed, and quality following participation in a high level agility and running program. This study demonstrates that individuals with TBI who meet our inclusion criteria can learn to run again and regain participation in recreational sporting activities as a result. Significant changes were seen in this study for running speed, HiMAT scores, and running quality. The training provided was also subjectively noted by participants and their family members to bring about improvements in lower-level functional tasks. Inconsistent changes in strength and no significant changes in running distance were noted. Each of the participants expressed personal satisfaction with the achievement of the goals they had put forth at baseline. It is our hope and belief that increased ability to participate in activities and social functions as a result of participation in this study will improve quality of life and give each participant motivation to maintain an active lifestyle.

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TABLES

Table 1. Participant one: baseline lower extremity PROM.

Muscle Group	Right	Left
Hip flexion	0-100°	0-100°
Hip extension	0-15°	0-10°
Hip internal rotation	WNL	0-15°
Ankle dorsiflexion	0-10°	-5°
Ankle plantarflexion	WNL	5-30°

All other upper and lower extremity PROM is WNL
PROM = passive range of motion; WNL = within normal limits

Table 2. Participant one: baseline upper extremity strength as assessed by MMT.

Muscle Group	Right	Left
Shoulder flexion	WNL	4+/5
Shoulder abduction	WNL	4+/5
Elbow flexion	WNL	Cannot isolate
Elbow extension	WNL	4/5
Wrist flexion	WNL	4/5
Wrist extension	WNL	4/5
Grasp	WNL	4-/5

MMT = manual muscle testing; WNL = within normal limits

Table 3. Participant one: baseline lower extremity strength as assessed by HHD in kilograms.

Muscle Group	Right	Left
Hip flexion	8.8	8.7
Hip extension	17.1	20.5
Hip abduction	9.9	10.9
Knee extension	12.2	3.8
Knee flexion	21.5	9.9
Ankle dorsiflexion	.6	0
Ankle plantarflexion	18.8	6.4

HHD = hand held dynamometry

Table 4. Participant one: baseline coordination testing.

Coordination Testing	Right	Left	Comments
Finger to nose	5	4	N/A
Finger to therapist's finger	5	4	N/A
Finger to finger	5	4	N/A
Finger opposition	5	3	N/A
Pronation/supination	5	3	N/A
Tapping foot	5	NT	Could not test due to decreased strength on the left

N/A = not applicable; NT = not tested

Key to Coordination Grading:

5 Normal performance

4 Minimal impairment: able to accomplish activity but with less than normal speed and skill

3 Moderate impairment: able to accomplish activity; movements are slow, awkward and unsteady

2 Severe impairment: able only to initiate activity without completion

1 Activity impossible

Table 5. Participant two: baseline upper extremity PROM.

Muscle Group	Right	Left
Shoulder internal rotation	WNL	0-10°
Wrist flexion	WNL	Pain at end-range
Wrist extension	WNL	Pain at end-range

All other upper and lower extremity PROM is WNL
PROM = passive range of motion; WNL = within normal limits

Table 6. Participant two: baseline upper extremity strength as measured by MMT.

Muscle Group	Right	Left
Shoulder flexion	4-/5	3+/5
Shoulder abduction	4-/5	3+/5
Elbow flexion	WNL	4/5
Elbow extension	WNL	4/5
Wrist flexion	WNL	4/5
Wrist extension	WNL	4/5
Grasp	WNL	4/5

All lower extremity measurements are WNL
MMT = manual muscle testing; WNL = within normal limits

Table 7. Participant two: baseline lower extremity strength as assessed by HHD in kilograms.

Muscle Group	Right	Left
Hip flexion	10.2	6.2
Hip extension	14.8	11.7
Hip abduction	13.9	12.7
Knee extension	27.0	10.7
Knee flexion	13.3	10.0
Ankle dorsiflexion	10.5	8.8
Ankle plantarflexion	11.9	23.6

HHD = hand held dynamometry

Table 8. Participant two: baseline coordination testing.

Coordination Test	Right	Left
Finger to nose	4	4
Finger to therapist’s finger	4	3
Finger to finger	NT	NT
Finger opposition	3	3
Pronation/supination	4	3
Tapping foot	4	3
Heel on shin	4	3

NT = not tested

Key to Coordination Grading:

5 Normal performance

4 Minimal impairment: able to accomplish activity but with less than normal speed and skill

3 Moderate impairment: able to accomplish activity; movements are slow, awkward and unsteady

2 Severe impairment: able only to initiate activity without completion

1 Activity impossible

Table 9. Participant three: baseline lower extremity strength as assessed by HHD in kilograms.

Muscle Group	Right	Left
Hip flexion	11.0	7.45
Hip extension	16.1	13.8
Hip abduction	10.0	8.5
Knee extension	8.35	4.25
Knee flexion	4.85	2.4
Ankle dorsiflexion	4.7	3.95
Ankle plantarflexion	15.0	2.0

HHD = hand held dynamometry

Table 10. Participant three: baseline coordination testing.

Coordination Test	Right	Left
Finger to nose	5	4
Finger to therapist's finger	NT	NT
Finger to finger	NT	NT
Finger opposition	NT	NT
Pronation/supination	5	4
Tapping foot	5	4
Heel on shin	5	4

NT = not tested

Key to Coordination Grading:

5 Normal performance

4 Minimal impairment: able to accomplish activity but with less than normal speed and skill

3 Moderate impairment: able to accomplish activity; movements are slow, awkward and unsteady

2 Severe impairment: able only to initiate activity without completion

1 Activity impossible

Table 11. Participant four: baseline upper and lower extremity strength as measured by MMT.

Muscle Group	Right	Left
UE strength throughout	5/5	4+/5
LE strength (excluding ankle)	5/5	5-/5
Ankle	5/5	4+/5

MMT = manual muscle testing

Table 12. Participant four: baseline lower extremity strength as assessed by HHD in kilograms.

Muscle Group	Right	Left
Hip flexion	11.3	11.5
Hip extension	28.3	32.2
Hip abduction	17.6	14.4
Knee extension	26.8	22.8
Knee flexion	8.6	12.1
Ankle dorsiflexion	9.0	10.6
Ankle plantarflexion	38.0	38.1

HHD = hand held dynamometry

Table 13. Participant four: baseline coordination testing.

Coordination Test	Right	Left	Comments
Finger to nose	5	4	Dysmetria
Finger to therapist's finger	5	4	Dysmetria
Finger to finger	5	4	Dysmetria
Finger opposition	5	4	N/A
Pronation/supination	5	4	Dysdiadokinesia
Tapping foot	5	4	Dysdiadokinesia
Heel on shin	5	4	N/A

N/A = not applicable

Key to Coordination Grading:

5 Normal performance

4 Minimal impairment: able to accomplish activity but with less than normal speed and skill

3 Moderate impairment: able to accomplish activity; movements are slow, awkward and unsteady

2 Severe impairment: able only to initiate activity without completion

1 Activity impossible

Table 14. Participant five: baseline upper and lower extremity flexibility measured by PROM.

Muscle Group	Right	Left
Shoulder flexion	0-118°	0-90°
Shoulder abduction	0-90°	0-90°
Hip abduction	0-20°	0-18°
Ankle dorsiflexion	0-1°	0-2°

PROM = passive range of motion

Table 15. Participant five: baseline upper extremity strength as measured by MMT.

Muscle Group	Right	Left
Shoulder flexion	3/5	3-/5
Shoulder abduction	3/5	3-/5
Elbow flexion	4/5	4-/5
Elbow extension	4/5	4-/5

MMT = manual muscle testing

Table 16. Participant five: baseline lower extremity strength as measured by MMT.

Muscle Group	**Right**	**Left**
Hip flexion	4-/5	4/5
Hip abduction	4-/5	4/5
Knee flexion	4-/5	4/5
Knee extension	4-/5	4/5
Ankle dorsiflexion	4-/5	3/5
Ankle plantarflexion	4-/5	3+/5

MMT = manual muscle testing

Table 17. Participant five: baseline lower extremity strength as assessed by HHD in kilograms.

Muscle Group	Right	Left
Hip flexion	0.05	0.05
Hip extension	2.6	7.2
Hip abduction	1.1	1.2
Knee extension	5.0	1.2
Knee flexion	0.2	0.0
Ankle dorsiflexion	0.0	0.0
Ankle plantarflexion	1.3	0.2

HHD = hand held dynamometry

Table 18. Participant five: baseline coordination testing.

Coordination Test	Right	Left
Finger to nose	4	4
Finger to therapist’s finger	4	4
Pronation/supination	4	3
Tapping foot	4	4

Key to Coordination Grading:

5 Normal performance

4 Minimal impairment: able to accomplish activity but with less than normal speed and skill

3 Moderate impairment: able to accomplish activity; movements are slow, awkward and unsteady

2 Severe impairment: able only to initiate activity without completion

1 Activity impossible

Table 19. Baseline participant characteristics reported before initiating the intervention.

Participant	Age (yrs)	Gender	Inpatient Stay (months)	Years after Injury	Presentation
1	Teens	Male	6	4	Hemiplegia Apraxic
2	20s	Female	7	6	Ataxic
3	20s	Female	3	5	Slight hemiplegia
4	30s	Female	7	16	Ataxic (one side) Slight apraxia
5	40s	Female	8	Less than 1	Apraxic

Table 20. Baseline patient characteristics.

Participant	Single Leg Stance (seconds)		Ability to Run	Goal
1	Not able to complete		20' with support (fell)	Run 200' to play baseball
2	R: 10	L: 4	10' CG	Run one hour
3	R: 10	L: 10	5 mins I	Run 5 mins Play soccer
4	R: 30	L: 15	40' I	Look "normal" when running Play tennis
5	R: 5	L: Unable	Unable	Walk and run normally

R = Right; L = Left; I = Independently; CG = Contact Guard

Table 21. Descriptive statistics and significant differences in running and functional mobility outcomes pre-test and post-test.

Running Distance (m)	Pre-test	384.60 ± 683.28
	Post-test	1400.60 ± 1722.83
Running Speed (m/sec)	Pre-test	2.71 ± 1.26
	Post-test	3.06 ± 1.21*
HiMAT	Pre-test	19.6 ± 11.89
	Post-test	27.60 ± 15.53*

* Significant differences identified pre-test vs. post-test (P < 0.05)

Table 22. Strength changes from pre-test to post-test as demonstrated by an 20% increase or decrease in hand held dynamometry measurements.

Participant	**> 20% Increase**	**> 20% Decrease**
One	R hip abd, L knee flex, R ankle df, ankle pf	Hip flexors, L hip abd, L knee ext
Two	Hip extensors, hip abductors, R knee flex, L knee ext, ankle dfs, R ankle pf	R knee ext, L ankle pf
Three	All muscles except R hip flex	
Four		All muscles except R pf
Five	Hip flexors, L hip ext, R knee flex, L knee ext, ankle dfs, ankle pfs	L hip abd

R = right; L = left; flex = flexion; ext = extension; df = dorsiflexion; pf = plantarflexion; abd = abduction

FIGURES

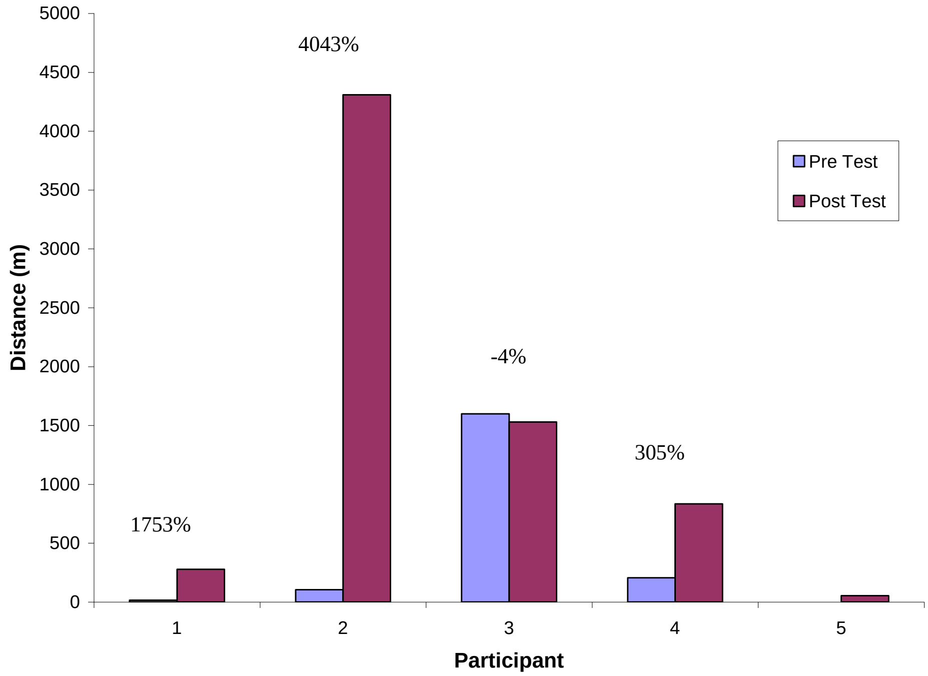

Figure 1. Change in running distance from pre-test to post-test in meters.

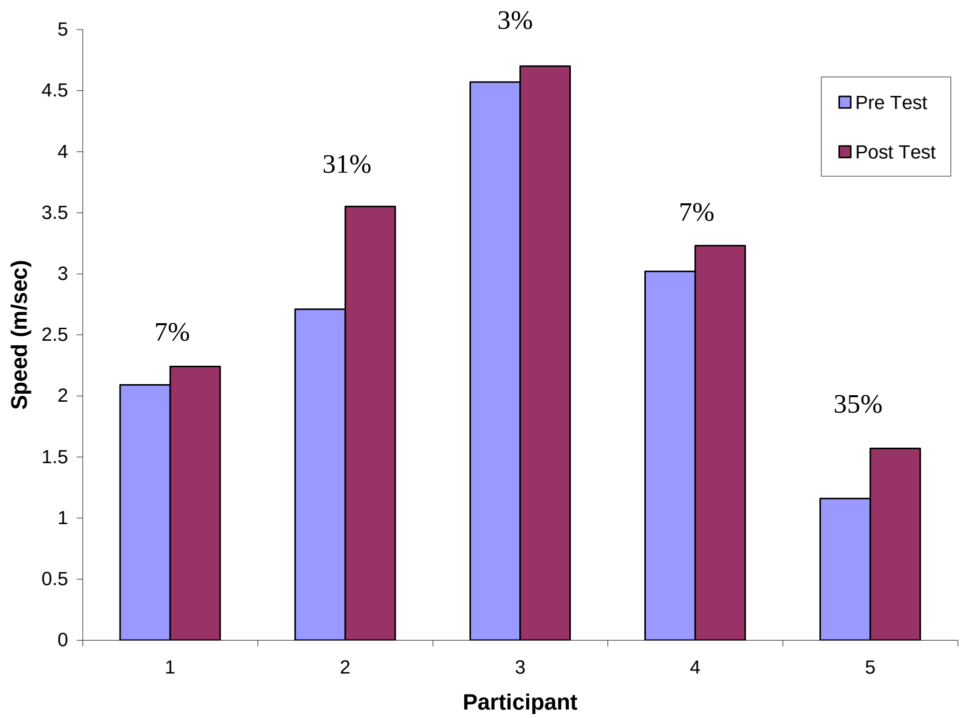

Figure 2. Changes in running speed (m/sec) from pre-test to post-test.

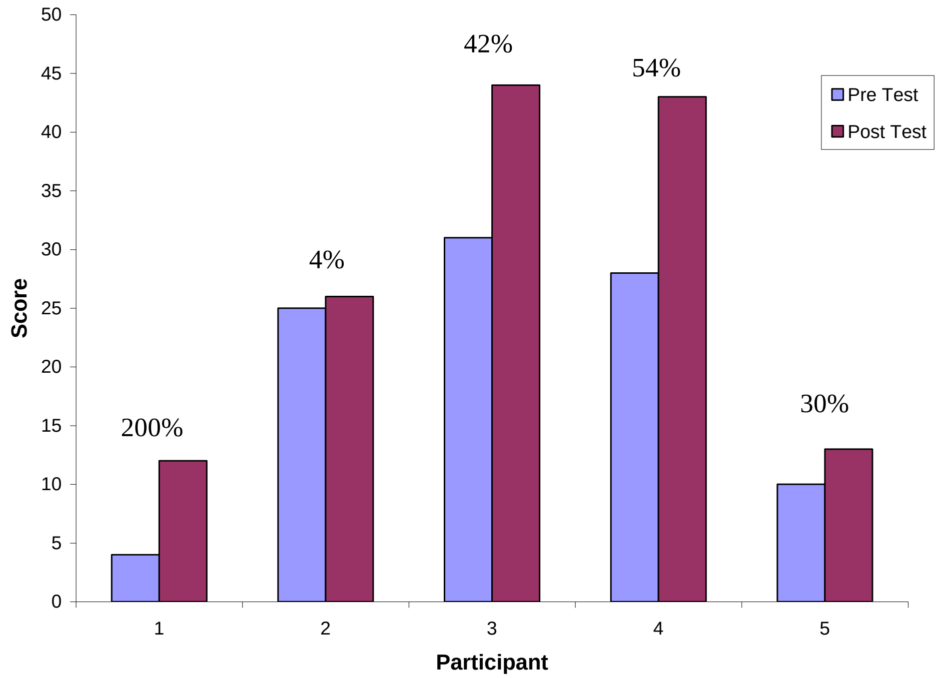

Figure 3. Changes in HiMAT scores from pre-test to post-test for each participant.

APPENDIX A: Screening Instrument

Study ID #
DOB:
Circle their response.

1. Has it been more than 6 months since your injury?
    a. Yes. Go to question #2
    b. No. Thank you, but you do not meet the criteria for this particular study.
2. Can you walk without an assistive device such as a cane, crutches or a walker?
    a. Yes. Go to question #3
    b. No. Thank you, but you do not meet the criteria for this particular study.
3. Can you cross the street and step up a curb?
    a. Yes. Go to question #4
    b. No. Thank you, but you do not meet the criteria for this particular study.
4. Can you walk 200 feet, about 1/3 of a block?
    a. Yes. Go to question #5
    b. No. Thank you, but you do not meet the criteria for this particular study.
5. Can you climb a standard flight of stairs?
    a. Yes. Go to question #6
    b. No. Thank you, but you do not meet the criteria for this particular study.
6. Do you have one side that is stronger than the other as a result of your injury?
    a. Yes. Go to question #7
    b. No. Thank you, but you do not meet the criteria for this particular study.
7. In the last 3 months, have you been hospitalized or gone to your doctor with any condition affecting your heart or blood pressure?
    a. Yes. Please explain.
    b. No. Go to question 9

8. Do you have a history of uncontrolled seizures?
    a. Yes. Thank you, but you do not meet the criteria for this particular study.
    b. No. Go to question 10.
9. Do you have any additional neurological diagnoses such as Parkinson's, stroke etc.?
    a. Yes. Thank you, but you do not meet the criteria for this particular study.
    b. No. Go to question 11.
10. Do you have any current orthopedic conditions, such as a broken bone, muscle or ligament strain etc.?
    a. Yes. Thank you, but you do not meet the criteria for this particular study.
    b. No. Go to question 12.
11. Are you currently, or expecting to become pregnant?
    a. Yes. Thank you, but you do not meet the criteria for this particular study.
    b. No. Go to question 13.
12. Do you have an allergy to tape?
    a. Yes. Depending on severity, enroll the participant.
    b. No. Enroll the participant.

APPENDIX B: The HiMAT: High-level Mobility Assessment Tool

INSTRUCTIONS

Subject suitability: The HiMAT is appropriate for assessing people with high-level balance and mobility problems. The minimal mobility requirement for testing is independent walking over 20m without gait aids. Orthoses are permitted.

Item testing: Testing takes 5-10 minutes. Patients are allowed 1 practice trial for each item.

Instructions: Patients are instructed to perform at their maximum safe speed except for the bounding and stair items.

Walking:	The middle 10m of a 20m trial is timed.
Walk backward:	As for walking.
Walk on toes:	As for walking. Any heel contact during the middle 10m is recorded as a fail.
Walk over obstacle:	As for walking. A house brick is placed across the walkway at the mid-point. Patients must step over the brick without contacting it. A fail is recorded if patients step around the brick or make contact with the brick.
Run:	The middle 10m of a 20m trial is timed. A fail is recorded if patients fail to have a consistent flight phase during the trial.
Skipping:	The middle 10m of a 20m trial is timed. A fail is recorded if patients fail to have a consistent flight phase during the trial.
Hop forward:	Patients stand on their more affected leg and hop forward. The time to hop10m meters is recorded.
Bound (affected):	A bound is a jump from one leg to the other with a flight phase. Patients stand behind a line on their less affected leg, hands on hips, and jump forward **landing on their more affected** leg. Each bound is measured from the line to the heel of the landing leg. The average of three trials is recorded.
Bound (less-affected):	Patients stand behind a line on their more affected leg, hands on hips, and jump forward **landing on their less affected** leg. The average of three trials is recorded.
Up stairs:	Patients are asked to walk up a flight of 14 stairs as they normally would and at their normal speed. The trial is recorded from when the patient starts until both feet are at the top. Patients who use a rail or a non-reciprocal pattern are scored on **Up Stairs Dependent.** Patients who ascend the stairs reciprocally without a rail are scored on **Up Stairs Independent** and get an additional 5 points in the last column of Up Stairs Dependent.
Down stairs:	As for Up stairs.

Scoring: All times and distances are recorded in the 'performance' column. The corresponding score for each item is then circled and each column is then subtotaled. Subtotals are then added to calculate the HiMAT score.

High Level Mobility Assessment Tool for individuals with TBI

SCORE							
ITEM	PERFORMANCE	0	1	2	3	4	5
WALK	sec	X	> 6.6	5.4-6.6	4.3-5.3	< 4.3	X
WALK BACKWARD	sec		>13.3	8.1-13.3	5.8-8.0	< 5.8	X
WALK ON TOES	sec		> 8.9	7.0 - 8.9	5.4-6.9	< 5.4	X
WALK OVER OBSTACLE	sec		> 7.1	5.4-7.1	4.5-5.3	< 4.5	X
RUN	sec		> 2.7	2.0-2.7	1.7-1.9	< 1.7	X
SKIP	sec		> 4.0	3.5-4.0	3.0-3.4	< 3.0	X
HOP FORWARD (AFFECTED)	sec		> 7.0	5.3-7.0	4.1-5.2	< 4.1	X
BOUND (AFFECTED)	1) cm 2) 3)		< 80	80-103	104-132	> 132	X
BOUND (LESS-AFFECTED)	1) cm 2) 3)		< 82	82-105	106-129	> 129	X
UP STAIRS DEPENDENT (Rail **OR** not reciprocal: if not, score 5 and rate below)	sec		>22.8	14.6-22.8	12.3-14.5	<12.3	
UP STAIRS INDEPENDENT (No rail **AND** reciprocal: if not score 0 and rate above)	sec		> 9.1	7.6-9.1	6.8-7.5	< 6.8	X
DOWN STAIRS DEPENDENT (Rail **OR** not reciprocal: if not score 5 and rate below)	sec		>24.3	17.6-24.3	12.8-17.5	<12.8	
DOWN STAIRS INDEPENDENT (No rail **AND** reciprocal: if not score 0 and rate above)	sec		> 8.4	6.6-8.4	5.8-6.5	< 5.8	X
	SUBTOTAL						

APPENDIX C: Hand-held dynamometry protocol

The plinth was placed with the short end against the wall. Dycem (or similar non-slip material) was placed between the plinth surface and mat, and between the mat and the participant's trunk to prevent slipping of the mat on the table and slipping of the participant on the mat. Two towel layers were added between the participant's body surface and the dynamometer to provide padding.

The therapist used 2 hands on the dynamometer, while an assistant stabilized the participant's body part where indicated. Two trials, lasting 5 seconds each with a 10 second rest period between, were performed. Details regarding therapist and patient position for MMT are explained below.

Manual muscle testing protocol for all lower extremity muscle groups.

Muscle Group	Participant Position	Therapist Position	Limb Position	Stabilized Body Part	Dynamometer Placement
Hip flexors	Supine, head toward wall	Kneeling on table, braced against wall with arms extended	Hip flexed to 90, knee relaxed	Trunk	Just proximal to knee on extensor surface of the thigh
Hip Abductors	Supine, head toward the wall	Standing, side of table of LE being tested, leaning into table	Hip and knee extended, hip in 0 abduction	Contralateral lower extremity*	Just proximal to knee on lateral surface of thigh
Ankle dorsiflexors	Supine, head toward wall pad dorsum of foot	Standing, facing patient, foot against table	Hip and knee extended, ankle neutral	Lower limb, proximal to ankle*	Just proximal to metatarsalphalangeal joints on dorsal surface of foot
Hip extensors	Supine, feet toward the wall, pad dynamometer	Kneeling on table, braced against wall arms extended	Hip flexed to 90, knee relaxed	Superior aspect of the shoulders	Just proximal to knee flexor surface dynamometer close to knee joint length across hamstrings
Knee extensors	Sitting in chair, pad under thighs and dynamometer	Kneeling in front, maintaining dynamometer position between leg and strap	Hip and knee flexed to 90; hands on thighs	Thigh with strap around seat of chair and both thighs; trunk with strap around trunk and back of chair	Strap around back leg of chair and anterior leg just proximal to joint on anterior surface. Dyanamometer placed between strap and anterior leg just proximal to joint
Knee Flexion	Sitting on chair	Kneeling, in front, with lower extremity braced against chair	Hip and knee flexed to 90; hands on thighs, ankle maintained in neutral position	Thigh with strap around seat of chair and both thighs; trunk with strap around trunk and back of chair	2" above calcaneous, posterior surface of leg, with fulcrum of dynamometer closest to joint
Ankle plantarflexion	Supine, feet at end of plinth, shoes off, 2"	Standing at foot of table, stabilize dynamometer	Hip, knee extension, neutral	Superior aspect of shoulders	Just proximal to 1st metatarsal head on ball of foot

(If participant can't complete heel raise)	from wall		dorsiflexion		
Ankle plantarflexion Measuring tool taped to wall, participant stands with lateral aspect of LE to be tested next to the wall	Standing with hands lightly resting on therapist's hands for balance	In front of participant with participant's hands resting on top of therapist's hands	Test leg extended, full weight bearing, Non-test leg, hip and knee flexed so patient is non-weight bearing on leg	Observe heel raise distance and stop participant if they meet criterion 1 or 2	Participant to perform single leg heel raises at the rate of 1 rep/2 seconds until**: 1. reaches 30 repetitions 2. heel raise is less than 50% of initial heel raise 3. patient pushes down on therapist's hands 4. knee flexes

**use metronome to determine rate

APPENDIX D: Frear-Moriello Running Gait analysis Instruction Form (converted from Excel spreadsheet)

Running Gait Analysis Form: What to look for

Stride (100%)				
Stance		Double Float	Swing	Double Float
Initial Contact	Mid Stance	Toe Off	Mid Swing	Initial Contact

Absorption:	Propulsion:	Initial Swing:	Terminal Swing:
Initial Contact: - Lateral heel contacts ground and then rapidly pronates (or some people land midfoot) -- As foot contacts ground, it is dorsiflexed (as opposed to walking where it plantarflexes) - Hip and knee flex to help decrease the force of the impact	**Toe Off**: - Maximal extension at ankle, knee, and hip	Ankle is dorsiflexed and knee is flexing almost the same time as toe off	Ankle is dorsiflexed
Mid Stance: -- dorsiflexion increases to 20 degrees by forward progression of the tibia - knee and hip begin extending - maximum pronation and then supination begins at heel off			
During all stages, look for symmetrical movement.	During all stages also look for arm movement: shoulder extension with the elbow straight back, then the arm comes forward and the hand moves slightly across the body (elbow should be <90 degress when forward, at 90 degrees while at side and >90 degrees when behind the body)	During all stages look at trunk: should maintain a forward lean throughout the running cycle, there should be minimal rotation, and the head should stay in neutral	During all stages there should be only be a slight change in vertical movement and COM (very similar as to walking)

APPENDIX E: Satisfaction with Life Scale

Survey Form: Below are five statements that you may agree or disagree with. Using the 1 - 7 scale below indicate your agreement with each item by placing the appropriate number on the line preceding that item. Please be open and honest in your responding.

- 7 - Strongly agree
- 6 - Agree
- 5 - Slightly agree
- 4 - Neither agree nor disgree
- 3 - Slightly disagree
- 2 - Disgree
- 1 - Strongly disgree

_____ In most ways my life is close to my ideal.

_____ The conditions of my life are excellent.

_____ I am satisfied with my life.

_____ So far I have gotten the important things I want in life.

_____ If I could live my life over, I would change almost nothing.

- 35 - 31 Extremely satisfied
- 26 - 30 Satisfied
- 21 - 25 Slightly satisfied
- 20 Neutral
- 15 - 19 Slightly dissatisfied
- 10 - 14 Dissatisfied
- 5 - 9 Extremely dissatisfied

APPENDIX F: Borg Rate of Perceived Exertion

6	no exertion at all
7	extremely light
8	
9	very light
10	
11	light
12	
13	somewhat hard
14	
15	hard (heavy)
16	
17	very hard
18	
19	extremely hard
20	maximal exertion

Sage Graduate Schools EDUCATION HEALTH SCIENCES MANAGEMENT

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April 6, 2010

Gabrielle Moriello
The Sage Colleges
Physical Therapy Department
45 Ferry Street
Troy, NY 12180

IRB PROPOSAL # 09-10-086R
Reviewer: Samuel W. Hill, Chair

Dear Ms. Moriello:

The Institutional Review Board has reviewed your application and has approved the revisions of your project entitled "Pilot study comparing partial body weight supported treadmill training and underwater treadmill training on running outcomes in those with traumatic brain injury." Good luck with your research.

When you have completed collecting your data you will need to submit to the IRB Committee a final report indicating any problems you may have encountered regarding the treatment of human subjects.

Please refer to your IRB Proposal number whenever corresponding with us whether by mail or in person.

Please let me know if you have any questions.

Sincerely,

Samuel Hill

Samuel W. Hill, PhD
Chair, IRB

SWH/nan

Cc. Alexandra Adams
Andrea Belanger
Jeffrey Collins
Dereck Silverman