EFFECT OF AN UNDERWATER TREADMILL TRAINING PROGRAM ON RUNNING OUTCOMES IN THOSE WITH TRAUMATIC BRAIN INJURY: A PILOT STUDY.

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Effect of an underwater treadmill training program on running outcomes in those with traumatic brain injury: a pilot study.

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ABSTRACT

Introduction: Research regarding rehabilitation of high level mobility activities, such as running, in individuals with traumatic brain injury (TBI) is limited. Re-learning how to run may help these individuals establish a healthier lifestyle and reduce secondary health complications. The purpose of this case series was to document changes in strength, running speed, running distance, quality of running, and high level mobility following a running rehabilitation program that included underwater treadmill training (UWTT) in individuals with TBI. ***Methods:*** Four individuals with TBI participated in a three phase, 15 week program. Phase 1 consisted of 6 weeks of strength, flexibility, balance, and agility exercises, Phase 2 consisted of UWTT, while Phase 3 consisted of over ground running and running specific drills. ***Results:*** Although individual changes were noted on almost all measures, participants did not demonstrate statistically significant improvements in running distance (p=.109), running speed (p=.068), or High-Level Mobility Assesssment Tool (HiMAT) scores (p=.068) from pre-test to post-test. Changes in running quality included improvements in dynamic balance, postural stability, stride length, arm swing, weight bearing, and hip control. Increases in strength of the hip abductors and knee extensors were found in all participants. ***Discussion:*** While no statistically significant improvements were found in running distance, running speed, or HiMAT scores, participants made individual gains, consistent to current research regarding patients with TBI. The intensity of the interventions likely contributed to individual improvements. ***Conclusion:*** Individuals with TBI can improve their ability to run using UWTT.

Suggested keywords: underwater treadmill training, traumatic brain injury, high-level mobility assessment tool, running

INTRODUCTION

According to the Centers for Disease Control and Prevention, it is estimated that over 1.7 million Americans sustain a traumatic brain injury (TBI) every year. TBIs resulted in 52,000 fatalities, 275,000 hospitalizations, and almost 1.4 million emergency room visits between 2002 and 2006.[1] TBIs also accounted for around 30.5% of all injury-related deaths during that period and impacted males more than females in every age category. The majority of TBIs (35.2%) were caused by a fall while 17.3% were contributed to motor vehicle traffic accidents.[1]

Individuals that sustain a TBI follow a pathway of care based on the severity of their injury. Some of these pathways may include discharge home from an emergency room, acute in-patient rehabilitation, long-term residential care facility, and/or other varying types of medical care needs. Rehabilitation is considered to be a particularly important aspect of post-hospital care. Early rehabilitation intervention following a TBI has been shown to be beneficial for physical improvement and return of self-care skills[2] as well as in preventing complications, and in facilitating overall recovery. While rehabilitation following a TBI may be successful at recovering functional abilities such as being independent in activities of daily living (ADL), achievement of these goals does not guarantee a return to sports related activities.[2]

The motor demands of sports related activities require a far greater degree of motor performance in comparison to the most common functional ADLs. A study by Rinneet al[3] compared the motor performance of physically well-recovered men with TBI with that of healthy men who had not encountered a brain injury. The study found men with a TBI had impaired balance and agility in comparison to those who did not have a brain injury. They also had difficulty starting and sustaining simultaneous rhythmical movement of the hands and feet, figure eight running, tandem walking, and fast rhythm coordination.[3] It is no surprise that an overwhelming majority (79%) of the individuals in the group with TBI reported that they had to change sporting activities and 4 members completely quit former sport activities due to deficits in balance, clumsiness in arm movements, difficulties in running and fatigue.

When compared with walking, running demands far more coordination, strength, balance, and motor control. The gait cycle can be divided into two parts, the stance phase and the swing phase. During walking, the stance phase accounts for 60% and the swing phase accounts for 40% of a full cycle. In contrast, with running, the stance phase is less than 50% of the cycle while the swing phase is greater than 50% of the cycle with specific percentages dependent upon running velocity.[4] Unlike walking, running does not have a period of double support but rather a period of double float, indicating a higher demand for balance and coordination.

The stance phase of running is further divided into initial contact, absorption, mid-stance, propulsion, and toe off. During initial contact and absorption, which is coupled as the eccentric half of the cycle, the foot pronates and the tibia internally rotates. At mid-stance the foot remains pronated, the tibia remains internally rotated, and the knee and hip joints flex. This occurs in order for the body to absorb ground reaction forces and to accommodate the uneven ground surface. During propulsion, these movements reverse resulting in calcaneal inversion, tibial external rotation and knee extension.[4-6]This occurs to allow increased stability of the foot and ankle, powerful and efficient push off, and forward limb propulsion.[6]

The swing phase begins with toe off and includes initial swing, mid-swing and terminal swing. Double float, a period when both feet are airborne, occurs twice during the swing phase, once at the beginning (first float) and once at the end (final float).[4,5] During toe off and initial swing, the ankle dorsiflexes and the knee and hip flex in order to provide ground clearance. The first float occurs throughout toe off and initial swing when both feet are airborne. The final float occurs during terminal swing and after maximum hip flexion is achieved. During this time, hip and knee extension are also occurring to allow descent of the limb to the ground surface. This portion of the running gait cycle is termed the concentric half.[4,5] Understanding correct biomechanics and phases of the gait cycle may help a runner prevent injury and improve running economy.

During running, the main muscles utilized are the hip flexors, quadriceps, hamstrings, gluteals, core muscles, gastrocnemius and the anterior tibialis - each serving a different purpose. The hip flexors concentrically contract to lift the leg into the air during swing. The gluteals and hamstrings assist with push-off into swing while the gastronemius powers to propel the leg forward during push-off. The gluteus medius and core muscles control stability of the pelvis and core to allow single leg stance and double leg float. The quadriceps stabilize the knee in stance phase and the anterior tibialis provides dorsiflexion to provide toe clearance during swing.[7-10]

People who have sustained a TBI typically have limitations in strength, balance, coordination and motor control.[11] Running is often a challenge for people post-injury because of the rapid alternative movements, high level of coordination and muscle co-activiation required.[8] Cognitive, emotional and behavioral deficits play a role as well,[11] as re-learning everyday activities and high level tasks requires motivation, emotional power, cognitive understanding and planning. Historically, once someone is able to walk they are discharged from rehabilitation, while higher-level mobility may continue to remain impaired.

Williams and Schache[12] highlighted the importance of high-level mobility training for those with TBI. High-level mobility includes the skills needed to functionally participate in social, leisure, sporting, and employment activities. Through two case studies, Williams and Schache[12] evaluated the use of a conceptual framework for retraining high-level mobility following TBI. The researchers used the High-Level Mobility Assessment Tool (HiMAT) as guidance for a training program. Interventions included high-level mobility training, general strength and cardiovascular fitness, additional physical and medical interventions. They found that high-level mobility activities, such as running, can be achieved post TBI.

Running can be described as a reciprocal movement activity requiring high levels of coordination, balance and strength in order to perform safely and efficiently. A training program focused on strength, balance, coordination and agility has been demonstrated to provide a successful base to retrain high functioning activities.[13] A running program should focus on re-educating reciprocal activities like walking, bounding, jogging, biking and skipping. Muscular strength and endurance are the building blocks required to perform reciprocal movements, balance training and agility coordination exercise. The basis of a running program should include a strength training protocol focused on the main muscles used with running. Both closed-chain and open-chain exercises are important within the functional pattern of running; closed-chain to establish weight bearing and open-chain to prepare for the strength required during the task.[14] A running program should follow a hierarchical framework of tasks beginning with simple and progressing to advanced.[15]

In order to achieve the goal of running, one must perform the actual activity as well as the training mentioned above. Individuals with TBI are at increased risk of falls due to impaired balance and coordination. Training over-ground as a sole intervention for recovery of running may provide more risk of injury. Body weight supported treadmill training (BWSTT) and underwater treadmill training (UWTT) are two alternatives to above ground running that may provide a safe and effective method of running training.

BWSTT is a useful therapy tool that has been utilized in various clinical settings for improving locomotor training and recovery of function. A body weight supported treadmill utilizes a harness that is attached to a lift. The lift, harness, and the individual can then be raised or lowered ultimately controlling the amount of unweighting of the person's total body weight. This allows the body weight supported device to assist and support with balance and postural issues that would normally require a significant amount of clinician assistance.[16]

Research has found favorable results using BWSTT in improving overground walking speed, endurance, stride length, cadence, balance, and stance symmetry while walking in individuals who have had a stroke.[17-23] In one particular study involving an individual with an incomplete spinal cord injury, the participant increased both over ground walking and running speeds suggesting its usefulness for rehabilitation in both walking and running.[23]

There are also favorable results regarding recovery of running ability following a brain injury. Miller[11] conducted a case study on a 38 year old man who experienced a stroke 2.5 years previously. The participant received an intensive BWSTT program at a frequency of 3 times per week for 8 weeks for a total of 23 sessions. At the conclusion of the study, he had gained strength, endurance, and the ability to return to recreational running.

In another case study, Moriello et al[24] used an intervention consisting of strength, balance, and agility training once weekly for 17 weeks, BWSTT training once weekly for 15 weeks, and a combination of overground locomotor training and strengthening exercise once weekly for six weeks in an adolescent male after TBI. Following the training, the subject demonstrated improved strength, running distance, running speed, quality of movement, and endurance. In an unpublished case series,[25]5 participants received a similar intervention. At a frequency of two times per week, the participants completed 6 weeks of strength training, 6 weeks of BWSTT, and overground running for 3 weeks. Improvements were noted in running speed, running distance, HiMAT score, and quality of running.

While there are only a small number of studies investigating the use of BWSTT, we found no studies that examined the use of UWTT as a therapeutic intervention for individuals with a TBI. UWTT is, essentially, a water enclosed treadmill that incorporates all of the benefits of both a treadmill and an aquatic environment. UWTTT encourages a person to maintain a steady speed, reciprocal lower extremity movement, and a symmetrical gait while the therapeutic properties of water allow the person to run with a reduced weight load. The buoyancy properties of water allow an individual to be unweighted, decreasing the gravitational demands of the running task and making running easier to perform. The amount of the body that is submerged in the water determines the load of weight bearing the person experiences. The hydrostatic pressure of water provides increased postural support, potentially benefiting people with TBI since they often have balance difficulties.[26] For people who are injured or are unable to meet the physical and neurological demands of running on the ground or on a treadmill, UWTT provides an alternative option in an environment that can be controlled and progressed to rehabilitate various patient needs.[27]

The Aquaciser III is an underwater treadmill system that has an exercise chamber, control panel, and water reservoir. A picture of the Aquaciser III is located in Appendix A. The UWTT environment is believed by many to be a fantastic rehabilitation tool that is useful for transitioning someone to land based running. Therapists may be better able to evaluate and correct an individual's running technique, if necessary, by a clear door on the side of the treadmill system which allows for viewing. The water temperature, depth, treadmill direction, and speed can all be controlled through a control panel on the side of the tank. Speed, level of incline, percent body weight support/depth of the water, and time on the treadmill can be recorded making data documentation feasible.

In addition, it has been found that participants that used UWTT had a significantly lower heart rate (HR) at any given maximal oxygen consumption compared with those running on a land-based treadmill.[26] This can be ideal for those with a compromised cardiovascular system which often happens as a result of damage to the brain centers that regulate cardiovascular responses to exercise in those with brain injury.

Due to the lack of research found in the literature in regard to UWTT and running in individuals with a TBI, the purpose of this study was to document outcomes following a strength, balance, agility, and running re-training program using UWTT for individuals with a TBI. We hypothesized that each participant would improve in running distance, running speed, quality of running, and high level mobility following the intervention.

METHODS

Sample

Four participants who fulfilled the inclusion and exclusion criteria were recruited for this study via word of mouth. The inclusion criteria included people who: (i) were post six months TBI, (ii) scored at least at Level IX on the Rancho Los Amigos Levels of Cognitive Functioning Scale, (iii) walked independently without a device, (iv) were community ambulators (able to walk 200’ up to a velocity of 0.3m·s-1, and could overcome low level obstacles such as curbs, uneven grounds, and stairs), (v) were primarily hemi-paretic, and (vi) had been cleared by a medical doctor to participate in an exercise program. The exclusion criteria included those who had, (i) any condition that indicated a contraindication for physical activity: history of myocardial infarction, uncontrolled or acute cardiac impairments, resting blood pressure of 200/110 or higher, resting O2 saturation rates <90%, resting HR <50 or >110 bpm, symptomatic postural hypotension, or uncontrolled metabolic diseases, (ii) uncontrolled seizures, (iii) any additional neurological diagnosis, (iv) any orthopedic conditions that were contraindicated or would prevent them from running (v) inability to run safely with a taping procedure without an ankle foot orthosis and (vi) pregnancy. All participants gave written consent.

Case Descriptions

Participant One (a 36 year-old male) sustained a TBI in a motorcycle accident. He was admitted to acute care for 2 weeks where he underwent a craniotomy. He then received acute rehabilitation for 6 months and lived in a nursing facility for 2 years. At that point, he was discharged home with a wheelchair, with the help of aids, and attended an outpatient adult Day Care program. He received Botox injections in his left hand and foot for about one year and also underwent tendon release surgery on his left foot. His past medical history (PMH) included a left finger fracture due to a fall, posterior collateral ligament surgery, seizures, and falls. His medications included Trileptol (150mg), Dilantin (50mg), and

InfatabP-D. He volunteered at a hospital 3 days a week. He went to the YMCA and trained in Fit Link circuits (mainly upper extremities) and rode a stationary bike 2 days a week. His goals were to be able to play with his 11 year old daughter, play basketball and have a normal gait pattern. He lived with his mother and daughter in a 2-story house. Prior to his injury, Participant One was independent in all ADLs and independent activities of daily living (IADLs)

At initial evaluation, his resting blood pressure and pulse rate were 100/70 mmHg and 84 bpm, respectively. Participant One presented with passive range of motion (PROM) limitations throughout bilateral UE's and lower extremities (LE's). See Table 1 and Table 2 for specific PROM measurements. He presented with greater strength deficits on the left side as compared to the right. See Table 3 and Table 4 for specific strength deficits. He exhibited hyper-reflexia at his left biceps, brachioradialis, and patellar tendon as well as a slight increase in muscle tone on the left.

Coordination testing was intact on the right side but he performed coordination activities with less than normal speed and skill on the left. See Table 5 for specific coordination data. Superficial sensation was intact except he had difficulty differentiating between warm and cold on both feet. Tactile localization was intact with the 5.07 monofilament throughout. His deep proprioception was intact at bilateral thumbs and knees, but not at the great toes bilaterally. Participant One was able to maintain tandem stance for 10 seconds with his eyes open. He was able to stand up to 2 seconds on his right leg but was only able to momentarily stand on his left leg.

At initial evaluation, he was independent with all bed mobility and sit to and from stand transfers from standard surfaces. He was able to transfer from the floor with supervision. He was able to ambulate community distances independently without a device. While walking, he exhibited no hip extension at terminal stance bilaterally, decreased trunk rotation, no arm swing on the left, decreased knee extension during mid stance bilaterally, decreased knee flexion during swing (right>left), a left hip hike and a trendelenburg gait. He was unable to run at initial evaluation. Participant One was able to independently negotiate a flight of stairs (with the use of railing), curbs, and ramps. He scored 12/54 on the HiMAT.

Participant Two (a 23 year-old female) sustained a brain aneurysm. She was admitted to the hospital with a bleed in her brain stem and left frontal lobe. She was on a ventilator for 2 weeks and her right side was initially flaccid. She had a g-tube inserted and a coil placed in her brain. Her intracranial pressure fluctuated widely during her acute care stay. She was admitted to rehab for 2 weeks and was discharged walking with a gait belt and an aide. She later received outpatient physical therapy for 5 months. She presented with some dysarthria. Her PMH included exercise induced asthma. Her goal was to be able to run again.

At initial evaluation, her resting blood pressure, heart rate, and oxygen saturation were 98/60 mmHg, 80 bpm, and 98%, respectively. Participant Two had deficits in short term memory. PROM of bilateral UEs/LEs were within normal limits (WNL). Right UE and LE strength was 4+/5 throughout except ankle dorsiflexion (4/5) and left UE and LE strength was normal. Reflexes were difficult to elicit and muscle tone was normal throughout. See Table 6 and Table 7 for specific strength measurement.

Coordination testing was intact on the right side but she performed coordination activities with less than normal speed and skill on the left. Light touch testing was intact throughout bilateral UE's and LE's. Deep proprioception and kinesthesia were intact at bilateral thumbs and great toes. See Table 8 for specific coordination data. She was able to maintain tandem stance for 20 seconds, stand on the left leg for 5 seconds and was unable to stand on the right leg. Participant Two was independent with mat mobility, sit to and from stand transfers from standard surfaces, community ambulation without a device, and negotiated a flight of stairs with railing support.

Participant Three (a 28 year-old male) sustained a severe TBI and left clavicle fracture when he was thrown from the back of a fire truck. He was in a coma for 9 days and spent one month in the intensive care unit. He spent close to 3 months in acute rehabilitation before receiving occupational therapy (OT), physical therapy (PT), and speech therapy 3 times a week as an outpatient. He also received pool therapy. He was a fireman prior to his injury. He was taking anti-seizure medications and Ritalin. He presented with dysarthria. PMH included surgery to prevent emboli, seizures and falls. His goal was to return to work and run again.

At initial evaluation, his resting blood pressure, heart rate, and oxygen saturation were 98/64 mmHg , 88 bpm, and 96%, respectively. UE and LE PROM was WNL. Muscle strength of the left side was generally greater than the right. See Tables 9, 10 and 11 for specific strength measurements.

Coordination testing was intact on the left side but he performed coordination activities with less than normal speed and skill on the right side. Superficial sensation and tactile localization were intact to light touch with a 5.07 monofilament throughout. Proprioception and kinesthesia were intact at bilateral thumbs and great toes. See Table 12 for specific coordination data. He was able to maintain tandem stance for 5 seconds. He was unable to maintain single-leg stance on the right LE, but was able to maintain it for 2 seconds on the left leg.

He was independent with bed mobility and sit to and from stand transfers from standard height surfaces. He was able to ambulate community distances without a device independently. He exhibited a wide base of support (BOS) and a stiff manner during ambulation. He was independent negotiating stairs with the support of a railing. He was able to transfer off the floor independently with UE support.

Participant Four (a 37 year-old male) sustained a TBI (frontal lobe damage) and left leg fracture after getting hit by a car. He remained in a coma for 2 months and was later transferred to acute rehabilitation for 2 months. He was discharged home with a wheelchair and needed assistance for ADLs. He received outpatient physical therapy services for several months. His PMH included wrist, arm, and leg fractures, bladder stones and a vasectomy. He worked in fiber optics prior to his injury. He did not exercise on a regular basis. His goal was to return to running, hunting, and fishing, as well as improve his ability to walk.

At initial evaluation, his resting blood pressure and HR were 122/84 mmHg and 96 bpm, respectively. He presented with moderate limitations with short term memory and used a smart phone to assist with this deficit. PROM was WNL except for limitations in bilateral ankle dorsiflexion. See Table 13 for specific ROM measurements. Muscle strength was generally greater on the left side as compared to the right. See Table 14 and Table 15 for specific strength measurements. His right bicep and brachioradialis reflexes were hyperreflexive and no increase in muscle tone was noted throughout.

Coordination testing was intact on the left side but he performed coordination activities with less than normal speed and skill on the right side. See Table 16 for specific coordination data. Superficial, deep, graphesthesia, and tactile localization (using the 5.07

monofilament) were intact throughout. He was able to stand on his right leg for 2 seconds and his left leg for 30 seconds.

He was independent with all bed mobility, sit to and from stand transfers from standard surfaces, and he ambulated community distances independently without a device. During gait, he presented with excessive bilateral heel strike, external rotation of his legs, had a slightly ataxic gait, and decreased arm swing bilaterally. He was unable to run at initial evaluation. He was able to negotiate 2 flights of stairs independently with support of a rail.

Protocol

This was a case series design and the protocol included three phases. Phases One and Three took place at The Sage Colleges, while Phase Two took place at The Albany Medical Center Outpatient Physical Therapy Department. All participants underwent interventions twice a week, for a total of 15 weeks. The duration of the interventions lasted approximately 1 hour and 15 minutes.

Phase One lasted 6 weeks and focused on strength, flexibility, balance, and agility activities aimed to prepare the participant for running. The programs were designed based on the American College of Sports Medicine criteria, which recommends people with TBI perform aerobic exercise 3-5 times a week, for 20-60 minutes, at an intensity of 13/20 (on the RPE Scale).[28] All exercises were chosen from a pre-generated list. Clinical judgment was made by the therapist to progress the participants from least to most difficult over the course of the intervention period. Each session began with a warm up, where participants walked for 5 consecutive minutes. Next, they performed 5 minutes of dynamic stretching which included split squats, walking lunges, hip pendulums, arm circles, and exaggerated kicking.

Following the warm-up, participants performed 15-20 minutes of static and dynamic balance training. These activities were progressed from double to single limb activities; single task to dual task; from ground to foam to half domes; and from eyes opened, to eyes closed. Next, participants performed 15 minutes of agility/plyometric exercises such as single and double leg hopping, bounding, agility ladder activities, high knees, butt kickers, and skipping.

Core and lower extremity strength training was performed for 10-15 minutes. Strengthening exercises performed were mainly closed chain activities such as forward/backward/side lunges, calf raises, and wall squats. Each exercise was performed for 6-8 repetitions, for 2-3 sets. Finally, each session concluded with a 5 minute cool down with passive stretching to all major muscle groups of the lower extremities (hip flexors, hamstrings, gluteals, IT band, quadriceps, and gastrocnemius muscles). The amount of time for each exercise left 10 minutes of rest for each participant. They were given the option to stand, walk or sit during rest periods.

Phase Two included underwater treadmill running using the Aquaciser III. Heart rate, blood pressure, pulse oximetry, and rate of perceived exertion (RPE) was obtained from each participant at the start of each session. Heart rate and pulse oximetry were monitored non-invasively using a sensor placed on the finger. Blood pressure was monitored using a standard sphygmomanometer and participants were asked to rate their exertion level on a scale from 6-20 using the Borg RPE Scale. A copy of the RPE Scale can be found in Appendix B.

Each participant completed one trial of the distance protocol and 2 trials of the speed protocol. The first session of the week was organized as distance/speed/speed; while the next session was speed/speed/distance. Vital signs were measured pre, during and post exercise. All participants began walking at their preferred speed on the treadmill. Participants ended with a 5-minute cool down, walking at their preferred rate of speed. If at the end of the 5-minutes, the participant's HR was not down to what it was after the warm up, the participant continued cooling down until their HR returned to resting values (or in the range it was pre-warm up).

Each speed trial began with a warm up, where the participant jogged or walked on the treadmill for one minute at their preferred speed. They were then instructed to run "at the fastest speed they could tolerate for 2 minutes." This was defined as the maximum speed where the participant had correct body mechanics as determined by the physical therapist and less than 10 scuffs. (*Scuffs* are defined as when the foot hits the treadmill during swing advancement. *Correct body mechanics* are defined as an upright and slightly forward trunk (or in some cases, backward), maximum hip extension, optimal step length and heel contact).

They were progressed when they were able to run at the maximum speed for 2 consecutive 4-minute trials and meet the criteria for progression (proper running mechanics, have less than 10 scuffs and did not stumble in the third minute of the trial). Water height was decreased in increments of 33% between the nipple line and the belly button. Once water height was at the level of the belly button, speed was then increased in increments of 0.2 mph each session. If they were not able to run at this speed by meeting the criteria the water level was increased one level as needed. In subsequent sessions, the amount of unweighting was decreased as per the protocol above before speed was increased. Each session then ended with a cool down where participants jogged or walked on the treadmill at their preferred speed for one minute; same as the first minute.

During the distance protocol, participants ran at a speed that they rated as an 11-12 on the Borg RPE Scale, and then during the last three weeks they ran at a rate of 13 on the RPE scale. The water height was the same as the speed trial. Participants ran at this speed for as long as they were able. If the participant demonstrated any sign of struggling, exceeded ACSM guidelines for vital signs, or they verbalized they needed to stop, the trial was terminated. Participants were encouraged to increase the distance every session.

The final phase, Phase Three, lasted 3 weeks. Phase Three was a combination of the first 2 phases that concentrated on overground running but also included strengthening exercises, flexibility exercises, and sport/leisure agility activities. Individual sessions began with a 5 minute warm-up, where the participants walked for 5 minutes.

Next, the participant performed 15-25 minutes of overground running. Each session consisted of 2 speed trials, each 25 meters. The participants were instructed to start running as fast as possible for 25 meters. In between trials, the participants walked 25 meters back to the starting line as a rest period. Next, participants performed one distance trial where they ran around a marked 50’ x 64’ area. They were instructed to run as far as they could for a maximum of 20 minutes. If during the course of the session, the participant demonstrated any sign of struggling the trial was terminated. The trial was also terminated if the participant exceeded ACSM guidelines or if they verbalized the need to stop. Vital signs were measured prior, during, and after exercise. After the overground running session was complete, the participant walked for 5 minutes.

Agility drills were then performed for 10-15 minutes. These drills incorporated specific sporting activities of interest to the participant (e.g. basketball, kickball, soccer, firefighting drills). Next, they performed 15-20 minutes of strengthening exercises (similar toexercises in the Phase One protocol). Each session ended with a cool down, that consisted of walking and static stretching, each for 5 minutes.

Instrumentation

Outcome measures included high-level mobility as measured by the HiMAT, lower extremity muscle strength as measured by hand held dynamometry (HDD), running distance, running speed, and quality of running. A trained physical therapist evaluated each participant. An initial evaluation was taken at baseline and re-evaluations were performed by the same therapist 3 weeks into Phase One, following Phase One, following Phase Two, and then at discharge. To prevent bias, the therapist was blinded from previous test results at re-assessments and discharge. Follow up measures were performed by phone 6 months following discharge.

High level mobility was measured using the HiMAT. It examines high-level mobility in participants with TBI beyond that of independent ambulation and includes 13 items that assess a wide range of high level activities including: walking, walking backwards, walking on toes, walking over an obstacle, running, skipping, hopping forward, bounding on the affected side, bounding on the less affected side, going up the stairs, and going down the stairs. Each item is scored on a scale 0-4 (based on the time/distance they receive). All items are then summed for a total score out of 54. Higher scores imply a higher level of performance. The administration of the test requires only 5-10 minutes. A copy of the HIMAT is located Appendix C.

The HiMat is a high-level mobility scale that is currently used in TBI rehabilitation to extend mobility to age-appropriate levels for return to leisure and sporting activities. The HiMat has very high interrater reliability and retest reliability, both with ICC values = 0.99.[29]

It has good internal consistency for individuals with neurological conditions (P=0.74).[14] It has good face and content validity (r=0.98).[30] It is a uni-dimensional scale with moderate to strong concurrent validity when compared to existing motor function scales such as the motor section of the FIM (r= 0.53, P<.001) and the gross function component of the Riverhead Motor Assessment (RMA) (r=0.87, P<.001) for measuring high-level mobility.[31]

Muscle strength of all major lower extremity muscle groups (ankle dorsiflexors, ankle plantarflexors, knee extensors, knee flexors, hip abductors, hip flexors, and hip extensors) was tested using the Nicholas handheld dynamometer. The dynamometer measured peak force during an isometric muscle contraction. Protocols for limb position, dynamometer placement, and stabilization of the subject are from the referenced article by Andrews et al,[32] with modifications based on results of a previous case study[24] which found poor reliability of knee extensors and ankle plantarflexors. Richard Bohannon was consulted regarding possible solutions to effectively evaluate the knee extensors and plantarflexors and he made specific suggestions for dynamometer placement and positons.[33]Per his input, such dynamometer placement modifications and positions can be found in Appendix D.

HHD is a reliable assessment technique if practiced by a single, experienced tester. Morris et al,[34] found good test-re-test reliability of HHD in people with TBI, when repeated tests took place within a single session. The test-re-test reliability was higher for muscles tested on the more affected side (r= 0.55-0.93) than muscles tested on the lesser affected side (r= 0.09-0.86). They concluded that when using the HHD, three trials are recommended in order to gain a true isometric measure of strength.

Results from a study performed by Arnold et al,[35] showed that HHD had good intra and interrater reliability for isometric strength at the knee and hip joints, but not ankle strength. They also demonstrated moderate to high correlation values when compared to other isometric dynamometry measures (r = 0.57-0.86; $p < 0.05$). Bohannon et al,[33] compared three dynamometer strength scores for each muscle group. The calculated correlations for pairs of strength for all muscle groups ranged from 0.84 to 0.99 from test 1 to 3 (ankle dorsiflexors= 0.99, plantarflexors=0.97, knee flexors=0.98, knee extensors=0.97, hip extensors=0.87, hip flexors=0.97). Such results demonstrated good to high reliability.

Running distance was measured on an indoor rectangular basketball court, measuring 94'x 50' (1 full lap = 288 feet). Cones were placed on each corner of the court and the participants were instructed to run for as long as possible. Each consecutive lap was added and a total distance was recorded. Reliability and validity values were not found in the literature relevant to determining maximal running distance in people with TBI. A graphic representation of the course used to measure running distance is located in Appendix E.

Maximal running speed was assessed through a timed 20m sprint using a stopwatch by timing the middle 10m of a 20m run. Participants were instructed to begin to run as fast as possible on the therapists command, "Go." The trial was recorded and converted to meters per second. In 2006, Duthieet al.[36] performed a study examining a 10 meter Sprint Test. They found the 10 meter sprint test has a marginal chance of reliably detecting a change of sufficient magnitude (<0.01 second, P=0.05) over a 10 meter distance.

Videotape analysis was used to determine the running quality across a 20 meter span from an anterior, posterior and sagittal view. The videotape was then analyzed by three experienced physical therapists. Therapists underwent intensive training, which emphasized what to look for in the participants gait during each phase of the gait cycle. Each skilled therapist followed the Moriello-Frear assessment form that included each phase of gait based on the analysis performed by Perry et al.[37] If two of the three therapists noticed deviations in the participant's gait, then it was considered real change. Sports Motion software was used to measure joint angles. The Sports Motion software measured angles from the markers placed on the lateral major bony prominences on the patient and recorded each. Appendix F describes specific marker placement on the patient during running analysis.

RESULTS

The study participants were 75% male and 25% female with a mean age of 31.5 years. The average inpatient stay was less than 2 months (1.75), while average number of years post injury was five years. Detailed baseline characteristics for all participants is located in Tables 17 and 18. All individuals completed the full 15 week protocol.

Results of Wilcoxen Signed Rank test did not reveal any significant improvements from pre-test to post-test in running speed ($p = 0.068$), HiMat scores ($p = 0.068$), or running distance ($p = 0.109$). See Table 19 for detailed results of the Wilcoxen Signed Rank test. Although there was no significant changes identified for the three dependent variables from pre-test to post-test, there were individual performance changes noted in each of the categories that showed a trend toward significance. For running distance, percent changes in individual running distance ranged from 0% to 842% from pre-test to post-test, as depicted in Figure 1. Participant Four was unable to achieve a period of double float in the gait cycle at the time of pre-test or post-test therefore a score of 0 was given for total distance at each measure. Percent changes in running speed ranged from 17% to 121% from pre-test to post-test, as depicted in Figure 2. The mean change in HiMAT scores from pre-test to post-test increased by 12.5 points upon post-assessment. Figure 3 depicts improvements in

HiMATscore from pre-test to post-test which range from 4 points (Participant One) to 23 points (Participant Three).

Changes in lower extremity strength from pre-test to post-test varied by participant, as reported in Table 20. Table 20 outlines the strength changes from pre-test to post-test as demonstrated by a 20% increase or decrease as measured by hand held dynamometry. There were consistent 20% increases in strength for the hip abductors and the knee extensors, with no consistency noted with 20% decreases in strength. Each participant increased strength by 20% in at least three muscle groups out of the eight tested, with two participants increasing strength by 20% in seven muscle groups out of the eight tested.

Through visual analysis of the gait pattern, gait quality was noted to improve for all participants. Throughout the running stride cycle, all participants demonstrated improved dynamic balance and postural control. Through visual analysis, Participant One showed increased heel strike, increased weight shift, improved weight bearing, more symmetrical trunk rotation, improved linearity of gait pattern, and improved weight shifting.

Through visual analysis, Participant Two showed equal and increased stride length, improved equality of arm swing, increased left heel strike during loading response, improved hip extension with toe off, and decreased bilateral lower extremity hip external rotation.

Through visual analysis, Participant Three showed increased and equal weight shifting, increased symmetry with arm swing, increased knee flexion and dorsiflexion, increased propulsion, increased eccentric control with dorsiflexion, decreased left lateral heel whip, demonstrated improved hip flexion and no trendelenburg of the left, and improved foot placement and linearity of gait. Participant Three improved but remained to lack equality with arm swing and stride length with left being less than right.

Through visual analysis, participant Four was more upright with improved trunk extension, showed increased control of left lower extremity and foot, demonstrated equal weight bearing, improved arm swing, showed midline foot placement, decreased trendelenburg, demonstrated decreased pronation in stance, showed decreased right hip external rotation in swing, and required less guarding demonstrating more postural control and improved dynamic balance. Participant Four, although close to achieving double float and flight, did not enter a true running gait pattern.

Overall, the trends noted in visual gait quality were improved dynamic balance and postural control, equality of and increased stride length, symmetrical foot placement, improved weight shift, decrease in trendelenburg and improvement in hip control, and equality of and increased arm swing.

In general, all participants had normal vital sign response to exercise. There was variability amongst participants in regard to pre-exercise and recovery heart rate trends. Participant Two's pre exercise HR was elevated, ranging from 85 bpm to 113 bpm, but responded to exercise with a normal increase and return to resting post. Participant One's HR, at times, took longer than 5 minutes to return to prior resting level as measured pre exercise. Participant Four's pre exercise HR was elevated, ranging from 99 bpm to 122 bpm, responded within normal ranges to exercise, and took longer than 5 minutes to return to prior resting level as measures pre exercise. Participant Four's blood pressure was inconsistently elevated at rest, during exercise, and post; showing no correlation to exercise intensity or any other observation or measured factor. All participants oxygen saturation was within normal values, ranging from 90 % to 99% saturation with pre, during, and post readings.

DISCUSSION

The purpose of this case series was to document and assess changes in strength, running speed, running distance, quality of running and high level mobility in individuals with a TBI, following a running re-training program that involved strengthening, balance, agility and running using UWTT. It is possible to achieve improvements in running ability and high level mobility skills through participation in an individualized, high-intensity mobility training protocol. While the highly specific 15-week training program failed to yield statistically significant results in the domains examined, participants made individual gains in each of the areas, which trended towards significance. All but one participant demonstrated the ability to run overground for greater distances, all participants demonstrated a faster running speed and improved HiMat score at post-test, and changes in strength of particular muscle groups were inconsistent.

There were no statistically significant changes in running speed from pre-test to post-test in the current study. However, the participants demonstrated an average 44% increase in overground running speed. Individual improvements may be attributed to the specificity and intensity of the training regime. Research has shown that traditional rehabilitation programs are not intense enough to produce training effects in individuals with TBI.[38] Phases One and Three of the exercise protocol were individualized to target existing deficits recognized in the participants. Once a deficit was identified, the exercise program was adapted to incorporate specific activities to target that deficit. All participants were encouraged to perform activities at a high intensity and with a high number of repetitions, which may have contributed to the improvements in running speed. As compared to a recent study by Moriello et al[24], used a similar exercise protocol combined with BWSTT, participants from that study yielded a

22.7% improvement in overground running speed. Perhaps, the increased resistance of the water during the UWTT added additional benefits that enabled participants to run faster when performing overground running.The large degree of variation in participant improvement in our program compared to the Moriello[24] study may be contributed to the program intensity, length and individual baseline characteristics (severity of injury, impairments, time since injury), which may have rendered improved results at post-test.

Additionally, unique exercise interventions have shown positive results in improving the 'work capacities' in people with TBI. Driver et al[39] examined flexibility, strength, endurance and work capacity of individuals before and after an aquatics program. They found that the aquatics group showed improvements in body composition, strength, and bike ergometry peak wattage time. These results may apply to our participants as well. The unique training the participants underwent during Phase Two of the protocol, the UWTTT, may have contributed to the increased strength, and ability to work harder, for longer. Inadvertently, the UWTT during Phase Two of the intervention may have contributed to the participants ability to run harder and faster during post-test speed testing.

There were no statistically significant changes in running distance from pre-test to post-test in the current study though three of the four participants increased their running distance. The group as a whole showed a mean increase of 497 feet in running distance which is almost 1/10th of a mile and a 282% increase. One participant did not achieve running status during the study as indicated by a failure to demonstrate double float during gait. Recent studies have reported statistically significant improvements in running distance in individuals with TBI and stroke following a task specific regime and an intense agility program.[11,24]

There are multiple possible factors contributing to the lack of statistical significance found in running distance in this study. Participant four never achieved running and therefore recorded 0 feet for both the pre-test and post-test. This data likely influenced the three other participants strong positive gains resulting in an overall non-significant change. Another possible factor is that this program was also a pilot study and therefore a small number of participants were recruited. Though a previous pilot study[25] which had a total sample size of 5 did achieve significance on several of their outcome measures, we had one less participant.

The HiMAT, which assesses higher-level mobility requirements of people with TBI for return to pre-accident social, leisure and sporting activities, is a uni-dimensional and discriminative scale for quantifying therapy outcomes.[40] An average improvement of 12.5 points in HiMAT scores from pre-test to post-test was noted among the 4 participants. According to the literature, the minimal detective change (MDC) for HiMAT is 4 points.[41] The observed change in HiMAT scores from pre-test to post-test in this study suggested a change beyond measurement error. The improvement observed in the HiMAT score may be a direct result of the 3-phase rehabilitation program that targets individuals with TBI who have high-level balance and mobility problems. Moreover, the program consisted of dynamic strengthening exercises that were similar to the items listed in the HiMAT. Thus, the improvement in the HiMAT score from pre-test to post-test was expected. These results are reflective of other studies using the HiMAT as an assessment tool for individuals with TBI participating in an exercise program. In a preliminary study, William & Morris[42]evaluated the efficacy of a high-level mobility program for twenty-eight individuals with acquired brain injury (ABI). The intervention included participating in the "Running Group" twice weekly for an hour over 3 months. An average of 9 point improvement in HiMAT scores was observed in individuals with TBI following a 3 month dynamic strengthening, agility, and plyometric exercises tailored to each individual. Williams & Schache[43] looked at the effects of a six month high-level mobility and over-ground running program on 2 individuals with contrasting clinical presentations recovering from TBI (a 52 year old male with hemiplegia and 24 year old male with ataxia). Using a conceptual framework for retraining higher-level mobility, both participants increased their scores on the HiMAT by 10 and 40 points, respectively.

Exercise is known to elicit a cascade of molecular and cellular processes that encourages and supports neuroplasticity. Neuroplasticity refers to the ability of the brain to adapt to environmental change, respond to injury and to acquire novel information by modifying neural connectivity and function.[44] Recent literature supports the theory that the brain is capable of re-organizing and regenerating for many years following an ABI.[44] Research suggest that acute aerobic, but not strength exercises increases basal peripheral brain-derived neurotrophic factor (BDNF) concentrations, although the effect is transient.[44] BDNF is protein that has a repertoire of neurotrophic and neuroprotective properties in the CNS and the periphery; namely, axonal and dendritic growth and remodelling, neuronal differentiation and synaptic plasticity.[43] Physical activity, particularly acute exercise seems to be the critical intervention to trigger the process which neurotrophins mediate energy metabolism and in turn neural plasticity. Of all the neurotrophins, BNDF seems to be the most susceptible to regulation by physical activity. Research has shown that BDNF is not only essential in the neuronal system, but is also intimately connected with central and peripheral molecular processes of energy metabolism and homeostasis.[44] Thus, it is imperative for post-TBI rehabilitation to focus on carrying out an intensive and repetitive training to induce neuroplasticity.

Lower extremity strength changes from pre-test to post-test were inconsistent among all of the participants and between left and right lower extremities in each participant. These inconsistencies may be attributed to individual threshold of fatigue, motivation, impairment and functional status at evaluation, severity of brain injury, and level of confidence. The hip extensors, hip abductors, knee flexors, knee extensors, and ankle plantarflexors muscles showed a consistent greater than 20% improvement from pre-test to post-test in at least 3 of the 4 participants. The extensors and plantarflexors are muscles typically utilized during overground running to propel the body forward. The abductors help stabilize the pelvis during running. In running, as the knee flexes following initial contact, the quadriceps contract eccentrically. This is seen as power absorption and reflects the knee flexors' essential role as shock absorbers.[4]These increases in muscle strength could be attributed to the respective exercises that were implemented during the intervention. The force production required to run and perform close chain exercise is derived from lower extremity extensor muscles.[45] These improvements were anticipated because participants were expected to perform a series of high-intensity close chain exercises that required the use extensor muscles for exercises that were power-driven.[45] On the other end, greater than 20% decrease in ankle dorsiflexors from pre-test to post-test was noted in 3 of the 4 participants.

Morielloet al[24] documented the outcome of a 3-phase rehabilitation program for a 17-year-old male with TBI in a case report. Moriello[24] et al found major improvements in bilateral hip extensors, bilateral knee extensors, and left ankle plantar flexors, which are the main muscles that propel the body during running. After completing a rehabilitation program consisting of strengthening and locomotor training, the 17-year-old male with TBI was able to run independently for one mile. Moreover, Miller et al[11] found at least 20% improvement in bilateral hip flexors and extensors, left hip abductors, and left ankle plantar flexors in a 38-year-old male following a stroke. The improvement in hip extensors, hip abductors, knee flexors, knee extensors, and ankle plantarflexors in this study were comparable. Additionally, in a study that looked at the effect of an intensive strengthening, agility and body weight supported treadmill training program on running outcomes in individuals with traumatic brain injury, Ingegni et al[25] found the muscles that appeared to show the most consistent improvements throughout the intervention included the hip extensors, hip abductors, ankle plantarflexors, and ankle dorsiflexors.

Changes in running gait quality were observed in all participants; with improved dynamic balance, improved postural stability, equality of stride length, increased and equal arm swing, equality of weight bearing, and improved hip control leading to decreased external rotation and trendelenburg being the most consistent between participants. These results are consistent with Williams[12] who used a twenty-four week high level mobility retraining program and Ingegni et al[25] who utilized a strengthening, agility, and BWTT program.

With individualized balance, agility, strength, and sport specific overground training our goal was to target specific limitations to allow development of the skill acquisition needed to perform efficient running. Our sample's improvement in running gait quality may be attributed to the UWTT program and the improvements in HiMAT and lower extremity strength, secondary to the individualized program encouraging symmetry and stability. Running under water has been shown to decrease the likelihood for injury while improving cardiorespiratory response like that of overground running. With the decreased stress placed on the body and the compressive forces of the water, running improvements were noted to appear quicker than when trained overground.[46] With the changes in running gait quality and efficiency noted, sport specific activities will be less energy demanding and more likely to be performed.

The study sample generally presented with a normal vital sign response to exercise for all three measured vital signs; heart rate, blood pressure, and oxygen saturation. Two participants did have elevated pre exercise heart rate, while one participant demonstrated elevated pre exercise blood pressure. TBI results in generalized deconditioning and possible autonomic dysfunction; both which could cause abnormal pre exercise, exercise, and post exercise return to pre exercise vital signs. The literature suggests that autonomic dysfunction is often present in the acute stages post traumatic brain injury, resolving typically by the subacute and chronic stages.[47] With all of our participants being in the chronic stage, this is less likely of an explanation for the abnormal pre exercise values. Also, autonomic dysfunction typically would alter vital sign exercise response, which our study subjects typically followed an expected vital sign exercise response. Elevated pre exercise heart rate could be attributed to many factorsincludungdeconditioning, anxiety, excitement; all possible explanations with our subjects.

Cardiorespiratory deconditioning is common sequelae post TBI secondary to hospitalization, periods of inactivity, and the increased likelihood for sedentary lifestyle post hospitalization.[48] It has been shown that 41% of community-dwelling people post TBI are sedentary, compared to 25% of the general non TBI population. Cardiorespiratory deconditioning results in poor heart and lung response to exercise and increased demand, demonstrated by elevated heart rate and blood pressure most commonly. Because our participants were all in the chronic phase, it is likely that cardiorespiratory deconditioning is the explanation for elevated heart rate and blood pressure pre exercise and increased time to return to pre exercise post.

Monitoring vital signs and symptoms throughout exercise and keeping close contact with our participant's primary care physicians regarding any concerns allowed safe practice. In addition, medications and their side effects could be another explanation for our vital sign findings. It is important for clinicians to monitor vitals for these reasons.

Limitations

This case series presents with several limitations. Perhaps the main limitation that decreased the cause effect was that this case series was part of a 3-year pilot study that aimed at recruiting 10 participants. Despite the recruitment effort, it was difficult to find participants that met our inclusion criteria and wanted to return to running and/or playing sports. Due to the variation in the severity of TBI injuries and a small sample size, the generalizability of the results of this study may be limited when applying to other individuals with TBI. It may be possible to further reduce variation amongst participants by including self-selected walking speed in the inclusion criteria. This study also lacks standardized protocol in regard to specific intervention activities such as strengthening activities. The design of the strengthening protocols were based on functional impairments among the participants. The strengthening protocol was tailored relative the deficits presented in each individual and therefore standardization is a difficult achievement.

Though much of the research mentions numerous factors which contribute to individuals increasing their running speed following specific exercise interventions, there are several factors which may have limited us to achieving significance during our study. First, we believe the small sample size (four participants) decreased the power to detect meaningful changes in running speed among participants. An article by Sandelowski[49] mentions that studies with small sample size may fail to support theoretical and meaningful change. While each participant improved their running speed from pre-test to post-test, the power of the study was low and we were unable to make assumptions based on these results. Additionally, participant four never achieved the ability to run, which also may have contributed to decreased statistical significance in our results.

The method used to assess strength may be a limitation. Morris[50] suggested using three trials of HHD; familiarization as the first trial and average the second and third to provide a typical measure of isometric muscular strength. However, this study use the average of 2 trials of HHD testing for each participants to account in order to get accurate measurement without fatiguing.

Further Research

It would be beneficial to see the interventions performed in this pilot program done on a larger scale with a larger sample size and a control group. Previous research studying UWTT in this population does not exist, so it is important to conduct further studies examining the benefits this population may gain from UWTT. A randomized control trial would best achieve adding to this current deficit. It is also suggested that newer robotic overground intervention devices such as KineAssist^{TM} and MABEL should also be included in running related traumatic brain injury research as newer technology continues to be developed that may be effective for retraining higher level activities.

While the inclusion and exclusion criteria in our study was rather specific for our purposes, there remains a great deal of variability in the individual effects and differences in individuals with TBI. In experimental research, it is difficult to account for the effect of the intervention if you do not control for the individual differences within a group. Minimizing within-group differences can be achieved with relevant and specific inclusion and exclusion criteria. While a standardized approach for return to running program containing high level activities in individuals with TBI may be appealing to determine a research effect, establishment of baseline guidelines for inclusion and exclusion of higher level activity in individuals with TBI seems more appropriate for purposes of determining clinical readiness for running rehabilitation.[51] It is believed that individuals with TBI can benefit from a more active lifestyle and participation in higher level activities therefore, thus it is critical for safe and appropriate parameters be established to help achieve this.

Since self-selected walking speed was found to be predictive of ability to run following TBI,[52] it would be interesting to include a self-selected walking speed assessment as an appropriate indicator for inclusion criteria in future running studies. While 1.0m/sec threshold appears to be at least a likely indicator, it would be useful for research purposes to confirm and control for self-selected walking speed in measuring running outcomes as well as determining the effects on walking speed. In addition, all of our participants verbally indicated that people were telling them that they were walking better.

Participant Four’s treatment program contained a focus on bounding and single leg stance activities. These activities were intended to carryover to and influence double float status during gait are have been reported as valid predictors of running ability in individuals with acquired brain injury.[15] After practicing the agility drills, attempts were made to carryover these skills into running. The researchers feel that with more treatment time, the participant would have achieved running status complete with periods of double float. Some people may require a variation in the level of intervention such as working on improving walking before they are ready to improve running. Running specific training would not be neurodevelopmentally appropriate for someone who has substantial impairments in walking.

We suggest that a QOL tool should be added to future research and include items in a broad category of health related aspects given that an acquired TBI can have a complex and comprehensive effect on an individual. Lastly, we would like to see more inclusion of the neurodevelopmental model in future research. The popularity of the neurodevelopmental evaluation and treatment approach for the orthopedic patient has only recently been researched.[60] Evidence from preliminary studies show that interventions in earlier developmental patterns and positions can have a positive effect on neurodevelopmentally based dysfunctions and asymmetries between upper and lower quarters and left and right extremities.[60] It would be interesting to see if there is any correlation, for example, in improving one's rolling ability and influencing their running outcomes. We would also suggest measuring all participants' baseline movement using a standard assessment such as the Functional Movement Screen or the Selective Functional Movement Screen.[61] The Functional Movement Screen quantifies movement through the scoring of seven movements based on neurodevelopment. The Selective Functional Movement is used when there is the presence of pain with movement and helps localize where there is mobility or a motor control stability problem at a particular location.

Conclusions

There continues to be limited literature regarding outcomes of running programs for individuals with TBI. The results of this pilot study and future planned studies will continue to contribute useful information to the world of neurorehabilitation. This study demonstrates potential for improvements in running related outcomes specifically mobility, strength, distance, speed, and quality following participation in a high level agility and running program. It is our belief that rehabilitation programs that go beyond basic ADLs and target a return to higher level recreational activities for individuals with TBI will naturally improve quality of life and result in positive health benefits for those involved.

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TABLES

Table 1. Participant one: Baseline upper extremity PROM.

Muscle Group	Right (^{o})	Left (^{o})
Shoulder flexion	WNL	150
Shoulder abduction	WNL	150
Shoulder internal rotation	WNL	30
Elbow extension	WNL	-30
Wrist extension	WNL	25

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

Table 2. Participant one: Baseline lower extremity PROM.

Muscle Group	Right (^{o})	Left (^{o})
Hip flexion	90	70
Hip extension	0	-10
Hip abduction	10	10
Hip internal rotation	30	30
Hip external rotation	40	WNL
Knee flexion	100	110
Knee extension	-10	WNL

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

Table 3. Participant one: Baseline upper extremity strength as assessed by MMT.

Muscle Group	**Right**	**Left**
Shoulder flexion	4/5	4/5
Shoulder abduction	4/5	4/4
Elbow flexion	WNL	4/5
Elbow extension	WNL	4/5

MMT = manual muscle testing; WNL = within normal limits

Table 4. Participant one: Baseline lower extremity strength as assessed by HHD.

Muscle Group	**Right (kg)**	**Left (kg)**
Hip flexion	14.9	10
Hip extension	19.3	23.9
Hip abduction	16.3	14
Knee flexion	15.9	7.8
Knee extension	23.2	32.5
Ankle dorsiflexion	12.4	7.8
Ankle plantarflexion	30.3	10.8

HHD = hand held dynamometry

Table 5. 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	4	N/A
Pronation/supination	5	3	N/A
Tapping foot	5	4	N/A
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 6. Participant two: Baseline upper extremity strength as assessed by MMT.

Muscle Group	Right	Left
Shoulder flexion	4+/5- out of 5	WNL
Shoulder abduction	4+/5- out of 5	WNL
Elbow flexion	4+/5- out of 5	WNL
Elbow extension	4+/5- out of 5	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	9.65	10.35
Hip extension	9.95	14.1
Hip abduction	12.05	15.95
Knee flexion	8.2	7.35
Knee extension	12.8	15.1
Ankle dorsiflexion	4.6	8.5
Ankle plantaflexion	25.9	23.45

HHD = hand held dynamometry

Table 8. Participant two: Baseline coordination testing.

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

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

Muscle Group	Right	Left
Hip flexion	5.3	3.3
Hip extension	10.1	14.3
Hip abduction	13.9	9.3
Knee flexion	5.9	7.3
Knee extension	5.3	8.2
Ankle dorsiflexion	5.0	4.1
Ankle plantarflexion	8.8	10.2

HHD= hand held dynamometry

Table 10. Participant three: Baseline upper extremity strength as assessed by MMT.

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

MMT= manual muscle testing

Table 11. Participant three: Baseline lower extremity strength as assessed by MMT.

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

MMT= manual muscle testing

Table 12. Participant three: Baseline coordination testing.

Coordination Testing	Right	Left	Comments
Finger to nose	4	5	N/A
Finger to therapist's finger	4	5	N/A
Finger to finger	4	5	N/A
Finger opposition	4	5	N/A
Pronation/supination	4	5	N/A
Tapping foot	4	5	N/A
Heel on shin	4	5	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 13. Participant four: Baseline upper and lower extremity PROM.

Muscle Group	Right	Left
Shoulder flexion	170	WNL
Shoulder abduction	170	WNL
Ankle dorsiflexion	0	0

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

Table 14. Participant four: Baseline upper extremity strength as assessed by MMT.

Muscle Group	**Right**	**Left**
Shoulder flexion	4+/5	WNL
Shoulder abduction	4+/5	WNL
Elbow flexion	4+/5	WNL
Elbow extension	4+/5	WNL

MMT = manual muscle testing; WNL = within normal limits

Table 15. Participant four: Baseline lower extremity strength as assessed by HHD in kilograms.

Muscle Group	**Right**	**Left**
Hip flexion	12.8	12.2
Hip extension	17.9	25.1
Hip abduction	20.2	21.2
Knee flexion	9.35	7.05
Knee extension	20.0	19.0
Ankle dorsiflexion	17.5	17.9

HHD = hand held dynamometry

Table 16. Participant four: Baseline coordination testing.

Coordination Testing	Right	Left	Comments
Finger to nose	4	5	N/A
Finger to therapist's finger	4	5	N/A
Finger to finger	4	5	N/A
Finger opposition	4	5	N/A
Pronation/supination	4	5	N/A
Tapping foot	4	4	N/A
Heel on shin	4	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 17. Baseline participant characteristics reported before initiating the intervention.

Participant	**Age (yrs)**	**Gender**	**Inpatient stay (months)**	**Years after injury**	**Presentation**
1	36	male	< 1 month	10	Left sided hemiplegia
2	23	female	<1 month	1 year	Right sided hemiplegia
3	28	male	3 months	< 1 year	Apraxic, right UE ataxia
4	39	male	2 months	8 years	Ataxic gait

Table 18. Baseline patient characteristics.

Participant	Single Leg Stance (seconds)		Ability to Run	Goal
	Right	Left		
1	2	Unable	Unable	Run 200' & participate in 5 minutes of basketball
2	Unable	5	NT	Run independently
3	Unable	2	NT	Run independently
4	2	30	Unable, fast walk	Run independently

NT = Not tested

Table 19. Pre-test and post-test descriptive statistics in running and functional mobility outcomes.

Running Distance (m)	Pre-test	321.75 ± 355.79
	Post-test	818.75 ± 825.00
Running Speed (m/sec)	Pre-test	2.66 ±1.11
	Post-test	3.84 ± 1.46
HiMat	Pre-test	19.25 ± 4.11
	Post-test	31.75 ± 8.62

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

Participant	> 20% Increase	> 20% Decrease
One	Hip ext, R hip abd, R knee ext, ankle pf	R hip flex, L knee flex, L knee ext, ankle df
Two	Hip flex, hip ext, hip abd, knee flex, knee ext, L ankle df, L ankle pf	R ankle df
Three	Hip flex, R hip ext, L hip abd, knee flex, knee ext, ankle df, ankle pf	L hip ext
Four	Hip abd, knee flex, R knee ext	R hip flex, ankle df, R ankle pf

R= right; L=left; flex =flexors; ext = extensors; df=dorsiflexors; pf=plantarflexors; df = dorsiflexors; abd=abductors

FIGURES

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

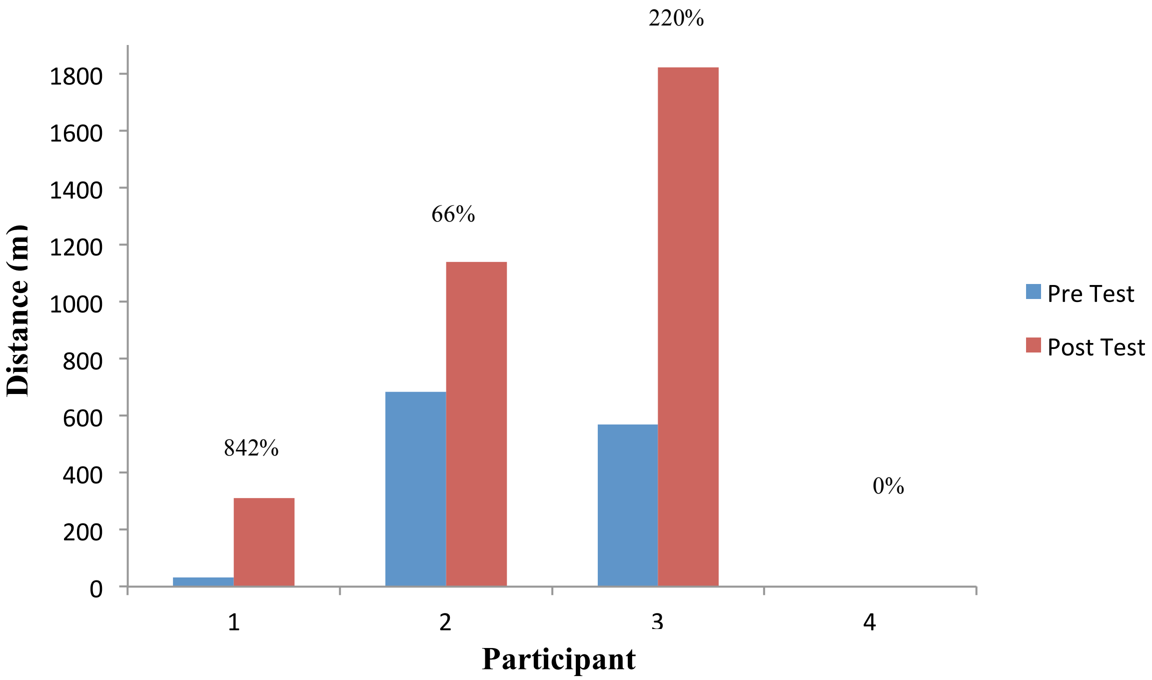


Figure 2. Changes in running speed (m/sec) from pre-test to post-test.

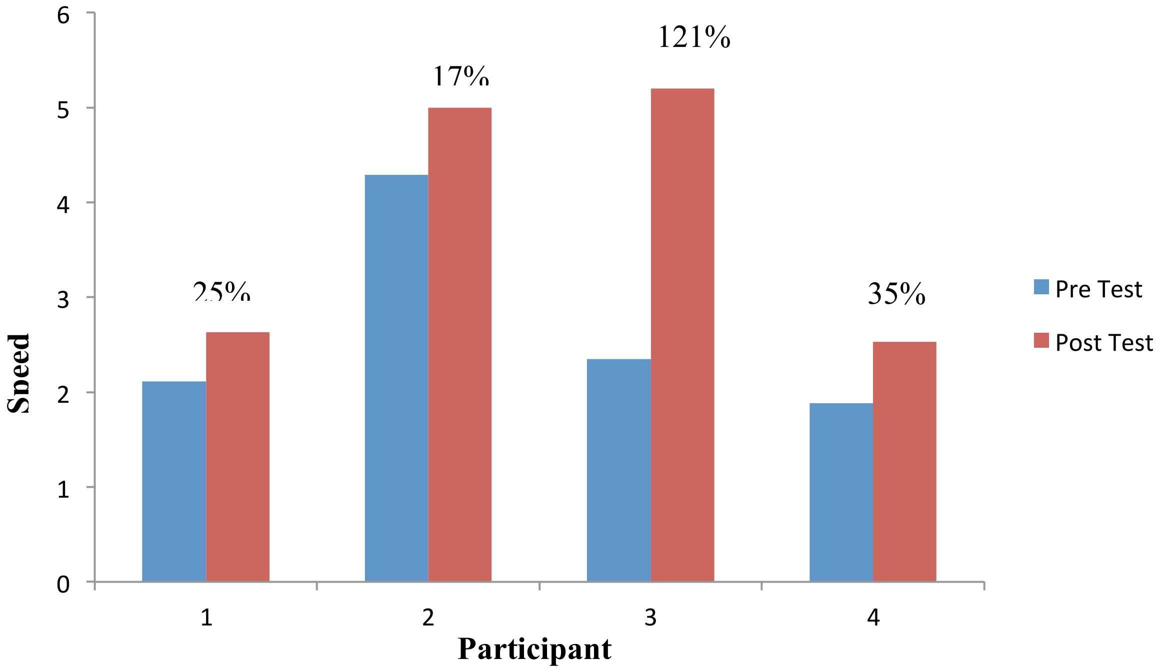
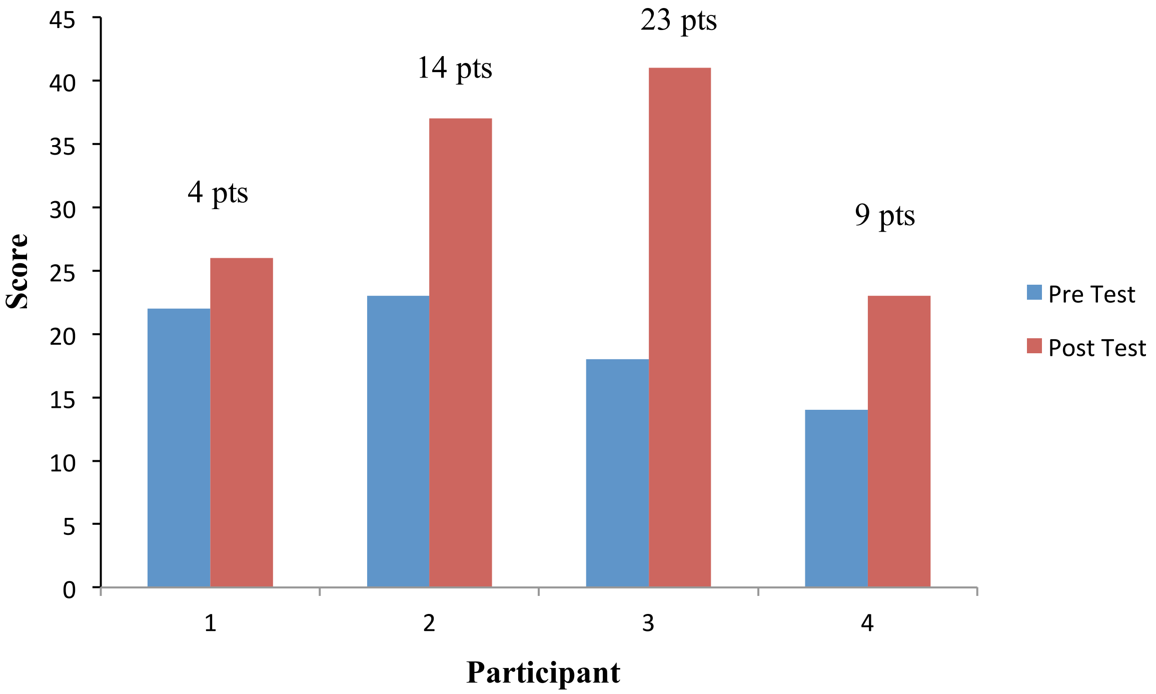


Figure 3. Changes in HiMAT scores from pre-test to post-test for each



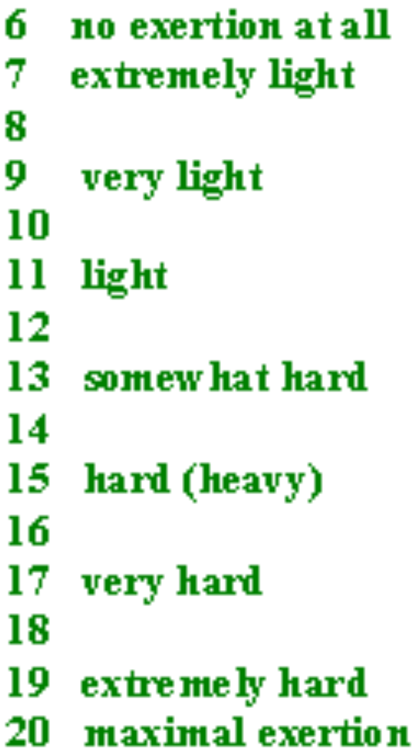
APPENDICES

Appendix A: Aquaciser III

http://www.hudsonaquatic.com/aquatic-systems-for-people/aquaciser-iii-underwater-treadmill-1

http://www.maxfit-movement.com/services.html

Appendix B: RPE Scale



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

http://www.examiner.com/article/basic-program-design-part-1-training-intensity

Appendix C: HiMAT: HIGH LEVEL MOBILITY ASSESSMENT TOOL

SCORE						
ITEM	PERFORMANCE	1	2	3	4	5
WALK	sec	> 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						

http://www.tbims.org/combi/himat/HiMAT.pdf

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/ 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

Appendix D : Manual Muscle Testing

The MMT outcome measures were based on the article by Bohanon[33] with modifications to the therapist position with an additional examiner for stabilization when necessary developed after incorporating information from studiesthat discussed further stabilization of resistance forces applied to the patient during the MMT. Modifications to the knee flexion and extension and plantarflexion tests are based on information from seminars.

Plinth set up: Plinth was placed with 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 mat on the table and participant on the mat. Padding the surface was done by adding 2 towel layers between body surface and dynamometer.

- Therapist used 2 hands on the dynamometer.
- Assistant stabilized participant's body part where indicated.
- There will be two trials with a 10 second rest period between each trial.
- Each trial will be for 5 seconds.

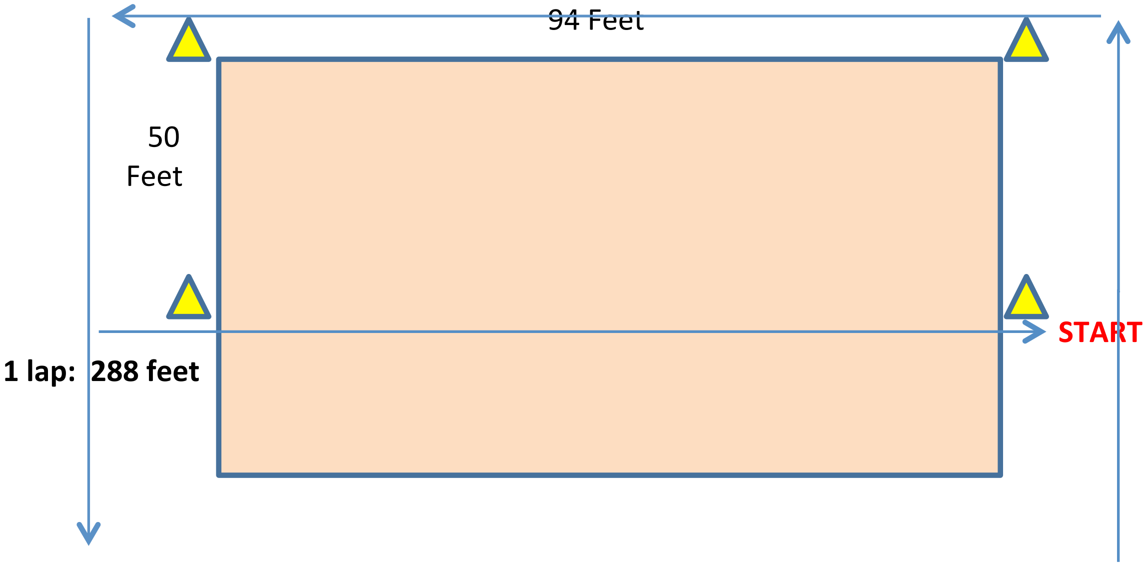
MMT was performed in the following order:

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 (If participant can’t complete heel raise)	Supine, feet at end of plinth, shoes off, 2” from wall	Standing at foot of table, stabilize dynamometer	Hip, knee extension, neutral dorsiflexion	Superior aspect of shoulders	Just proximal to 1st metatarsal head on ball of foot
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

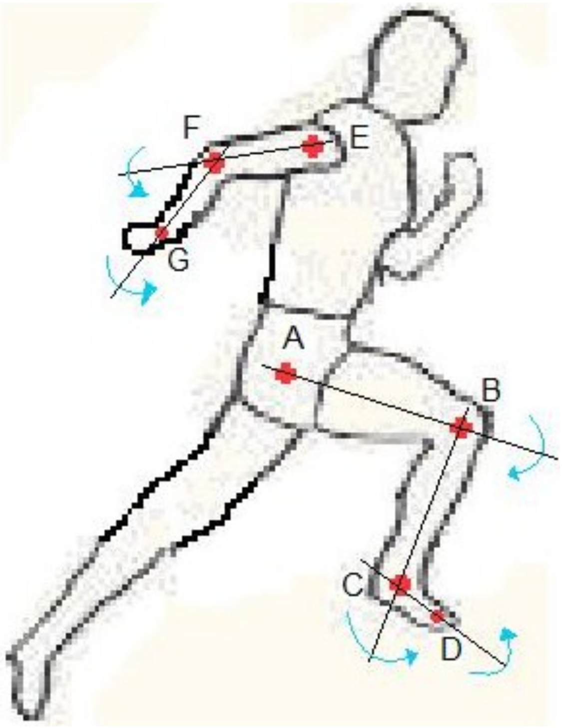
<u>Appendix E</u>: Distance Protocol

The participant ran in a marked rectangular area x 288' as far as they were able.

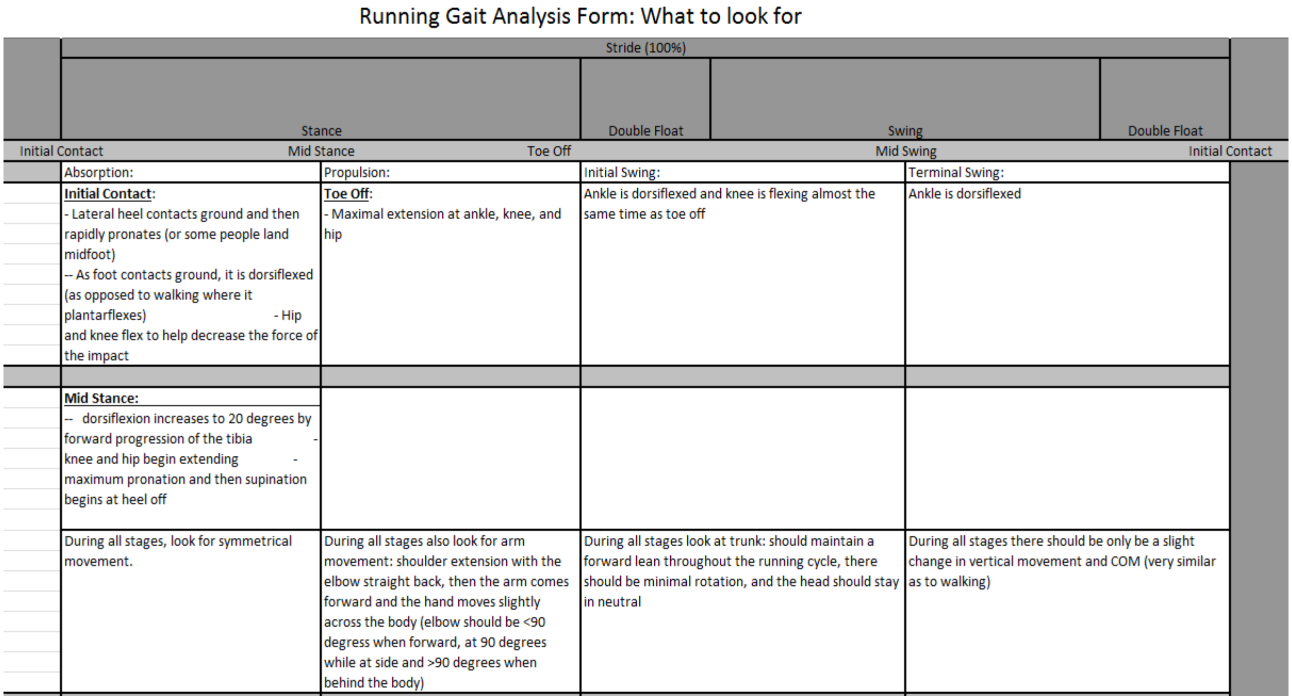


Appendix F: Quality of running

Quality of running will be determined by videotape analysis which will occur at week l, week 6, week 12 and week 15. Markers were placed on the lateral body prominences. If changes in gait were noticed by the skilled therapists, angles were measured to determine amount of change.



Appendix G: Frear&Moriello Gait Analysis form



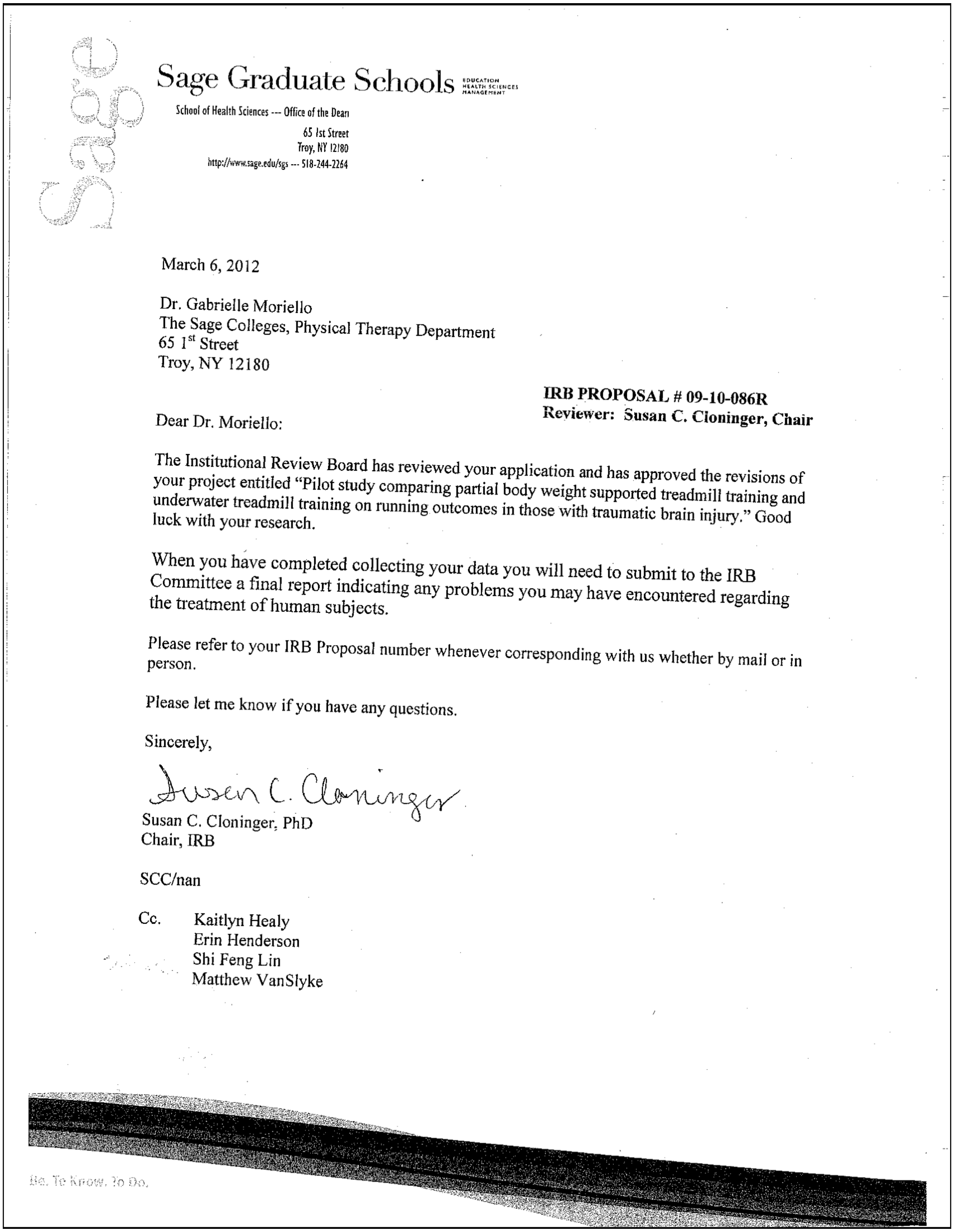
Running Gait Analysis Form: What to look for

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)



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March 6, 2012

Dr. Gabrielle Moriello
The Sage Colleges, Physical Therapy Department
65 1st Street
Troy, NY 12180

IRB PROPOSAL # 09-10-086R
Reviewer: Susan C. Cloninger, Chair

Dear Dr. 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,

Susan C. Cloninger

Susan C. Cloninger, PhD
Chair, IRB

SCC/nan

Cc. Kaitlyn Healy
Erin Henderson
Shi Feng Lin
Matthew VanSlyke

Be. To Know. To Do.