Feasibility of Ballistic Strength Training to Improve Mobility of Inpatients with Traumatic Brain Injury

Izel Gilfillan  BPhty (Physiotherapy)
Department of Physiotherapy, School of Healthcare Sciences, Faculty of Health Sciences, University of Pretoria, Pretoria, South Africa

Diphale J. Mothabeng  PhD (Rehabilitation)
Head of Department, Department of Physiotherapy, School of Healthcare Sciences, Faculty of Health Sciences, University of Pretoria, Pretoria, South Africa

Annelie van Heerden  MPhysio (Physiotherapy)
Department of Physiotherapy, School of Healthcare Sciences, Faculty of Health Sciences, University of Pretoria, Pretoria, South Africa

ABSTRACT

The objective of this study was to investigate the feasibility of ballistic strength training (BST) to improve the mobility of individuals recovering from traumatic brain injury (TBI) in an inpatient rehabilitation centre. Participants had a maximum of eight usual physiotherapy sessions substituted with BST sessions. The feasibility of BST was assessed in terms of recruitment, attendance, adverse events (AEs), and participant acceptability of the intervention. The clinical aspects of feasibility were assessed by recording the ability of participants to complete the exercises and acquire skills. Secondary measures included the 10-metre walk test, the 6-minute walk test, and the Global Rating of Change scale. Fourteen of 22 eligible individuals with TBI in an inpatient rehabilitation centre consented to participate in the study, of whom two were excluded. No intervention-related AEs occurred. Participants attended 97% (71/73) of the total sessions. Participants positively accepted the intervention as rated on a visual analogue scale, M (SD) = 9.2 (0.9). All participants were able to complete the BST exercises. Participants significantly improved comfortable walking speed and walking capacity (p < 0.01). Participants perceived a meaningful change in walking ability. BST appears to be a promising rehabilitation method that may improve the walking outcomes of individuals with TBI in an inpatient rehabilitation setting. Larger-scale clinical trials are warranted.


Key Words: Ballistic Strength Training, Locomotion, Mobility, Rehabilitation, Traumatic Brain Injury

INTRODUCTION

Traumatic brain injuries (TBIs) are a major cause of mortality and long-term disability, often with complex clinical presentations (Vella et al., 2017), including mobility limitations (Walker & Pickett, 2007; Williams & Willmott, 2012). Mobility limitations include reduced walking speed, reduced walking distance, and impaired quality of gait (McFadyen et al., 2003). Mobility limitations are also associated with poor community participation and reduced health-related quality of life (Williams & Schache, 2010).

Evidence suggests that early intensive rehabilitation may speed up recovery (Zhu et al., 2007) and mitigate deficits following TBI (Archer et al., 2012). Rehabilitation should include intensive practice and task specificity to attain improvements following central nervous system injury (Hornby et al., 2020; Kleim & Jones, 2008; Peters et al., 2014).

The recovery of walking ability is considered a key aspect of TBI rehabilitation (Katz et al., 2004; Walker & Pickett, 2007; Williams et al., 2009). Greater walking capacity enhances a person’s activities of daily living, enables them to cross roads or access their community (Charrette et al., 2016), and facilitates participation in recreational activities (Katz et al., 2004; Wilson et al., 2019).

Individuals with neurological conditions struggle to walk mainly because of muscle weakness and/or reduced power production (Nadeau et al., 1999; Williams et al., 2013), necessitating strength training as a core component of physical rehabilitation. Despite the importance of strength training for people with neurological conditions, optimal methods and best practice have not been identified. Slow and heavy progressive resistance training programmes have been shown to improve muscle strength (the maximum force a muscle can produce) but fail to translate into function, such as improved walking ability (Dorsch et al., 2018; Williams, Kahn, et al., 2014). One reason for this could be that muscle function for walking requires rapid force generation or muscle power (the rate at which a force is produced) (Williams et al., 2013; Williams, Kahn, et al., 2014). Ballistic (i.e., fast) strength training (BST) is a form of strength training aimed at improving muscle power generation (Williams et al., 2019), which is relevant for walking in the field of neurorehabilitation (Hendrey et al., 2018; Van Vulpen et al., 2017). BST commonly includes a jump or non-contact phase. The benefits of BST for improving task-specific performance were acknowledged in a recent systematic review on the effects of BST in TBI and other neurological populations, such as stroke, Parkinson’s disease, and multiple sclerosis (Cordner et al., 2020). The review highlighted that, although BST seems promising for
improving muscle strength, power generation and mobility, the results were inconclusive and warranted further investigation. To the best of our knowledge, the effects of BST in the TBI population have only been studied in a later recovery phase in outpatient settings (Cordner et al., 2020; Williams & Ada, 2022; Williams, Clark, et al., 2014) and cannot be generalised to inpatient rehabilitation settings. The potential benefits of BST for motor learning and neuroplasticity (Williams et al., 2019) warrant further investigation, particularly in the early recovery phase following TBI.

This study primarily determines the feasibility of a BST-based treatment approach in an inpatient TBI rehabilitation setting. As a secondary objective, we investigated the impact of BST on improving walking outcomes. We hypothesised that the intervention would be feasible and that individuals with TBI in an inpatient rehabilitation centre would show improved mobility.

**MATERIALS AND METHODS**

**Study design and participants**

This feasibility study followed a quasi-experimental single-group pre-test–post-test non-randomised design. The study was conducted in a New Zealand specialist acquired brain injury inpatient rehabilitation setting. All participants provided written informed consent before participating in the study. Reporting was conducted in accordance with CONSORT recommendations for pilot and feasibility studies (Eldridge et al., 2016). The study procedures followed the principles of the Declaration of Helsinki. The study was registered with the Australian New Zealand Clinical Trials Registry (trial registration number ACTRN126120107389).

Physiotherapists who were familiar with the study protocol identified potential participants. The severity of brain injury was classified according to the Glasgow Coma Scale (GCS, as documented on arrival to the emergency department) and the duration of post-traumatic amnesia. Moderate TBI was indicated with an initial GCS of 9 to 12 out of 15 and a post-traumatic amnesia duration of 1 to 6 days. Severe TBI was indicated by an initial GCS of 3 to 8 out of 15 and a post-traumatic amnesia duration of 7 or more days. If there was a difference between the severity level for the GCS and the duration of post-traumatic amnesia, the more severe category was used (New Zealand Guidelines Group, 2006).

Ambulatory individuals with moderate to severe TBI, admitted for inpatient rehabilitation, were screened for eligibility and recruited consecutively. The eligibility criteria were (a) first-ever diagnosis of moderate to severe TBI, (b) less than 6 months post-injury, (c) 18–65 years of age, (d) independent, unaided baseline mobility before TBI, and (e) able to walk with standby assistance of one person for 14 m or longer with or without assistive devices and orthoses. Individuals were excluded if they (a) were unwilling or unable to consent, (b) had severe cognitive or behavioural problems that prevented assessment, (c) were medically unstable (preventing cardiovascular exercise), (d) had had spinal surgery in the last 6 weeks or had recent orthopaedic injuries restricting weight-bearing, (e) had lower limb muscle weakness from a peripheral cause, (f) had any previously diagnosed central nervous system disorders, (g) if walking was not their preferred mode of indoor mobility, or (h) if they were able to walk independently, unaided with a comfortable walking speed faster than 1.55 m/s after the TBI. We recruited participants over 6 months, from February to July 2022.

**Ballistic strength training**

Following enrolment and baseline assessments, participants had two 30 min BST sessions instead of two 30 min conventional physiotherapy sessions per week. Participants attended BST sessions for at most 4 weeks (maximum of eight sessions), representing the typical inpatient length of stay. Discharge planning from the rehabilitation centre was not influenced by study participation.

The BST sessions were held in the therapy gym located at the rehabilitation centre. Sessions were individually supervised by a physiotherapist or physiotherapy assistant trained in the BST programme. The BST intervention was based on the theoretical framework designed and tested by Williams et al. (2019). The BST intervention aimed to improve muscle power generation, targeting the main muscle groups responsible for forward propulsion when walking (Hendrey et al., 2018; Williams et al., 2019). The exercises focused on quick movements with light loads at high repetition. Each training session followed a two-part structure. Part A was completed on a slide-board (jump trainer, Total Gym), and part B was completed within parallel bars using a mini-trampoline and a 10 cm high step. Each part was composed of four exercises, 2 min in duration, with a 2 min rest break between each part. Participants alternated between starting each session with part A or part B. Therapists were allowed to give hands-on assistance if necessary to provide mediolateral ankle stability and to facilitate push-off if required. Participants were monitored closely and guided with feedback. Rest breaks were initiated by the participant or the therapist. This was to ensure the correct quality of movement if the technique deteriorated.

The progression of exercises depended on the participant’s ability to perform the correct movement at the target velocity. The target velocity was guided by a metronome set at one repetition per sec, the typical time for a usual gait cycle, for five of the eight exercises in the programme. The load was increased once the participant met the performance criteria. The exercise programme and progression principles are available in Appendix A.

**Assessments and outcome measures**

**Feasibility and acceptability**

We measured feasibility by assessing the ability to recruit participants, participants’ attendance of BST sessions, the safety of the BST sessions, and whether participants found the intervention acceptable. A screening log Excel spreadsheet was used to record the rate at which participants were recruited to the study. We kept an exercise log for each participant, recording session attendance, adverse events, the order of the exercise programme followed (starting with part A or with part B), the progression of exercises (whether the correct movement pattern was performed, if the target speed of movement was met, and if the load such as the level of incline on the jump trainer applied), orthoses used, and whether manual assistance was required from the therapist during the exercises. Skills acquisition was determined by a participant’s ability to
accurately complete all BST exercises under supervision only. Safety was determined by recording any adverse events (AEs) using the Common Terminology Criteria for Adverse Events (National Cancer Institute, 2017). We monitored AEs during BST sessions and during the trial period.

Participants’ acceptability of the intervention was evaluated after completion of the BST intervention (Lamontagne et al., 2014; Tverdal et al., 2018). Participants were asked to rate their agreement with the following statement: “I find the BST programme acceptable” on a visual analogue scale (10 cm line) (Lamontagne et al., 2014; Tverdal et al., 2018). Higher scores indicated greater acceptability of the intervention.

Walking outcomes
Walking outcomes were measured using the 10-metre walk test (10MWT) and the 6-minute walk test (6MWT). The 10MWT is a standardised measure of walking speed (m/s). In TBI, this test shows excellent test-retest reliability (Tyson & Connell, 2009; van Loo et al., 2004). Using a 50 m pathway, participants were instructed to walk as safely and quickly as possible. The study used a minimally clinically important difference of 0.175 m/s for comfortable walking speed in the stroke population (Fulk et al., 2011).

The 6MWT measures distance (m) walked over 6 min as a sub-maximal test of aerobic capacity and walking endurance. The test shows excellent test re-test reliability for the TBI population (Mossberg, 2003; van Loo et al., 2004). Using a 50 m pathway, participants were instructed to walk as safely and quickly as possible. These assessments (the 10MWT and 6MWT) were performed with shoes on and with their usual gait aid or orthosis. A physiotherapist, trained and accredited to use the Functional Independence Measure (FIM), completed the locomotion item of the FIM at baseline (pre-test) and repeat assessment (post-test).

Following the intervention, we measured whether participants perceived a change in walking ability using the Global Rating of Change scale (GRoC), which is a 15-point ordinal scale (Kamper et al., 2003). Participants rated their perceived change in walking ability from 15 (great deal worse) to positive seven (a very great deal better).

Data analysis
Data were analysed in consultation with an independent statistician using Microsoft Excel and R Windows Version 4.2.1 (R Core Team, 2018). The level of significance was set at 0.05. Baseline characteristics and feasibility measures were summarised using descriptive statistics, namely mean and standard deviation, or median and interquartile range. We adapted the traffic light system from Campbell et al. (2020) to assess the feasibility of the BST intervention and to decide whether the intervention should be evaluated in a full trial. Green indicated implementation was feasible and the study design will require minor or no change. Amber indicated an element would require major modification before progressing, and red indicated it would not be feasible to progress to a full trial with the study design (Gilfillan et al., 2023).

Baseline and post-intervention walking outcomes were compared using a t-test or Wilcoxon test. Incomplete datasets were excluded from the analysis (Figure 1).

RESULTS
Feasibility for progression to a full-scale trial

Recruitment capability
Over a 6 month period, 28 participants were screened, of whom 22 individuals met the inclusion criteria. Of these 22 individuals, 14 consented to participate, while six were not approached (due to short length of stay or staff shortages), and two declined to participate because they were afraid of delayed discharge despite being assured otherwise. Of eligible individuals (n = 22), 14 (64%) consented to participate. Participants’ demographic information is summarised in Table 1.

Of the 14 initial participants, 12 completed the study protocol. One participant was lost before the baseline assessment due to government COVID-19 isolation regulations. One participant was lost to post-intervention assessment due to a medical complication unrelated to the study (Figure 1). The traffic light stop-go criteria were amber for recruitment capability over the trial period.

Attendance, participant safety, and intervention acceptability
Overall, attendance rates were excellent (71 of 73 total possible training sessions across all the participants, 97%). One participant could not attend two gym sessions during their time of participation due to being a household contact of someone with COVID-19, which at the time required mandatory isolation for one week. Participants attended a M (SD) of 5 (2) of 8 potential training sessions. There were no AEs during the trial period. All the participants positively evaluated the acceptability of the BST intervention (visual analogue scale, M = 9.0, SD = 0.9).

The traffic light stop-go criteria results were green for training attendance, participant safety, and intervention acceptability.

Clinical aspects of feasibility
All participants were able to complete the BST programme. The majority of the 71 completed sessions were performed under supervision only (n = 49, 69%). Participants required manual assistance to the ankle from a therapist to ensure correct movement while performing exercises in 22 sessions (31%). Most participants achieved skills acquisition during the trial period. Eleven participants acquired the desired skills for all four exercises in part A (slide-board exercises; progression ranged from 30% to 50% of body weight), and eight participants acquired skills for all four exercises in part B (full bodyweight exercises). Skills were acquired sooner in part A of the programme. The traffic light stop-go criteria were green for clinical aspects of feasibility.

Preliminary changes in walking outcomes
Compared to baseline measures, participants improved significantly (p < 0.01) in both the 10MWT and 6MWT after the intervention (Table 2 and Figure 2). All the participants achieved independent mobility and were able to walk unaided by the end of the intervention. Changes between baseline and post-test walking parameters are captured in Table 2. Participants...
Two conventional physiotherapy sessions per week replaced by two BST sessions (n = 13)

Repeat assessments (n = 12)
Lost to follow-up due to medical complication (n = 1)
Discontinued intervention/withdrew (n = 0)

Two patients refused consent
Six patients deemed competent to consent but not approached:
- Length of stay/discharge (n = 5)
- Staff shortage (n = 1)
participants signified that our eligibility criteria were adhered to the protocol demonstrating the practicability of the BST intervention. The absence of voluntary withdrawals led to the study and was able to continue using a supportive abdominal binder, which was in keeping with the training protocol. Few AEs have been reported in other studies on ballistic strength training in people with neurological conditions (Cordner et al., 2020; Taylor et al., 2005).

In our study, participants did not experience any AEs, suggesting that BST was well tolerated by participants and that individuals recovering from TBI in an inpatient rehabilitation centre are motivated to improve their walking ability.

Training attendance was excellent, with participants attending 71 of 73 total sessions. Two participants missed one session each, one due to COVID-19 isolation regulations and one due to non-COVID-19-related illness. The high attendance rate suggests that BST is safe for individuals in early recovery from TBI.

In our study, participants positively accepted the intervention, motivating them to improve their walking ability. Training attendance was excellent, with participants attending 71 of 73 total sessions. Two participants missed one session each, one due to COVID-19 isolation regulations and one due to non-COVID-19-related illness. The high attendance rate suggests that BST was well tolerated by participants and that individuals recovering from TBI in an inpatient rehabilitation centre are motivated to improve their walking ability.

In the inpatient recovery phase of TBI. All the participants adhered to the protocol demonstrating the practicability of the BST intervention. The absence of voluntary withdrawals of participants signified that our eligibility criteria were appropriate and that the BST intervention, focusing on fast movement at low load and high repetitions, was viable. All the participants were able to perform all eight of the prescribed exercises, demonstrating that the exercises were targeted at an appropriate level. Participants acquired skills more quickly and were able to progress at a faster rate for the four exercises performed on the slide-board in part A of the exercise programme. These exercises were all performed below body

### Table 1

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>n</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, in years (M, SD)</td>
<td>43</td>
<td>15</td>
</tr>
<tr>
<td>Gender</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>13</td>
<td>93</td>
</tr>
<tr>
<td>Female</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>Ethnicity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Asian</td>
<td>4</td>
<td>29</td>
</tr>
<tr>
<td>European-New Zealander</td>
<td>4</td>
<td>29</td>
</tr>
<tr>
<td>Māori</td>
<td>4</td>
<td>29</td>
</tr>
<tr>
<td>Other European</td>
<td>2</td>
<td>14</td>
</tr>
<tr>
<td>TBI classification</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moderate</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Severe</td>
<td>14</td>
<td>100</td>
</tr>
<tr>
<td>Glasgow Coma Scale (out of 15)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3–8</td>
<td>3</td>
<td>21</td>
</tr>
<tr>
<td>9–13</td>
<td>8</td>
<td>57</td>
</tr>
<tr>
<td>14–15</td>
<td>3</td>
<td>21</td>
</tr>
<tr>
<td>Length of PTA, in days (Mdn [IQR])</td>
<td>26 [16, 49]</td>
<td></td>
</tr>
<tr>
<td>Length of stay, in days (Mdn [IQR])</td>
<td>29 [22, 52]</td>
<td></td>
</tr>
<tr>
<td>Mechanism of injury</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recreational activities</td>
<td>5</td>
<td>36</td>
</tr>
<tr>
<td>Assault</td>
<td>4</td>
<td>29</td>
</tr>
<tr>
<td>Vehicle</td>
<td>3</td>
<td>21</td>
</tr>
<tr>
<td>Fall</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>Pedestrian</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>Orthopaedic injuries</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skull fractures</td>
<td>8</td>
<td>57</td>
</tr>
<tr>
<td>Upper limb fracture</td>
<td>5</td>
<td>36</td>
</tr>
<tr>
<td>Rib fractures</td>
<td>3</td>
<td>21</td>
</tr>
<tr>
<td>Spinal fracture/subluxation</td>
<td>2</td>
<td>14</td>
</tr>
</tbody>
</table>

Note: PTA = post-traumatic amnesia; TBI = traumatic brain injury.

*Unless otherwise indicated.

### Table 2

<table>
<thead>
<tr>
<th></th>
<th>Pre-test</th>
<th>Post-test</th>
</tr>
</thead>
<tbody>
<tr>
<td>10MWT in m/s (Mdn [IQR])</td>
<td>1.2 [1.0, 1.3]</td>
<td>1.4 [1.4, 1.6]</td>
</tr>
<tr>
<td>6MWT in m (Mdn [IQR])</td>
<td>473 [373, 511]</td>
<td>575 [499, 614]</td>
</tr>
<tr>
<td>FIM locomotion score (n, %)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 (minimal assist)</td>
<td>3 (25)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>5 (supervision)</td>
<td>7 (58)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>6 (modified independence)</td>
<td>0 (0)</td>
<td>1 (8)</td>
</tr>
<tr>
<td>7 (independent)</td>
<td>2 (17)</td>
<td>11 (92)</td>
</tr>
</tbody>
</table>

Note: 10MWT = 10-metre walk test; FIM = functional independence measure.
Table 3
Traffic Light Progression Criteria Used to Decide if the Ballistic Strength Training Feasibility Trial Could Be Up-Scaled to a Full-size Trial

<table>
<thead>
<tr>
<th>Progression criteria Measurement</th>
<th>Green (Proceed)</th>
<th>Amber (Consider changes)</th>
<th>Red (Stop)</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recruitment capacity</td>
<td>15–20</td>
<td>10–14</td>
<td>&lt; 10</td>
<td>14</td>
</tr>
<tr>
<td>Number of participants recruited</td>
<td>&gt; 70%</td>
<td>50–69%</td>
<td>&lt; 50%</td>
<td>64% Amber</td>
</tr>
<tr>
<td>Proportion of eligible participants consented</td>
<td>&gt; 75%</td>
<td>50–75%</td>
<td>&lt; 50%</td>
<td>97% Green</td>
</tr>
<tr>
<td>Attendance</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of BST sessions attended per participant</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adverse events: incidence, type, and severity</td>
<td>Minor modifications made to BST to accommodate discomfort.</td>
<td>AEs in a large proportion of the sample size.</td>
<td>Occurrence of serious AEs.</td>
<td>No AEs Green</td>
</tr>
<tr>
<td>Acceptability</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intervention acceptability: Visual analogue scale</td>
<td>Most participants (&gt; 50%) find BST acceptable (&gt; 5/10).</td>
<td>Conflicting views on the acceptability of BST, or major revisions needed.</td>
<td>Most participants (&gt; 50%) find BST unacceptable (&lt; 5/10), or changes required are not feasible.</td>
<td>100% Green</td>
</tr>
<tr>
<td>Participant safety</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skills acquisition: Assistance and speed of movement. Data collected from participant exercise logs (part A and part B)</td>
<td>Most (&gt; 50%) participants require supervision. Most participants achieve skills acquisition during the intervention period.</td>
<td>&lt; 50% of participants require assistance. Conflicting results on skills acquisition.</td>
<td>Most (&gt; 50%) participants require assistance. Amount of assistance required is not feasible. Changes required are not feasible.</td>
<td>Supervision only (69%) Skills acquisition Part A (92%), part B (67%) Green</td>
</tr>
<tr>
<td>Clinical feasibility</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Participants’ ability to complete BST (yes/no)</td>
<td>Most participants can complete BST.</td>
<td>Participants can participate with minor adjustments.</td>
<td>Most participants are unable to complete BST.</td>
<td>100% Green</td>
</tr>
<tr>
<td>Skills acquisition: Assistance and speed of movement. Data collected from participant exercise logs (part A and part B)</td>
<td>Most (&gt; 50%) participants require supervision. Most participants achieve skills acquisition during the intervention period.</td>
<td>&lt; 50% of participants require assistance. Conflicting results on skills acquisition.</td>
<td>Most (&gt; 50%) participants require assistance. Amount of assistance required is not feasible. Changes required are not feasible.</td>
<td>Supervision only (69%) Skills acquisition Part A (92%), part B (67%) Green</td>
</tr>
<tr>
<td>Indication of effect on mobility outcome measures</td>
<td>Clinically important change between pre-test and post-test.</td>
<td>Minimally clinically important change between pre-test and post-test.</td>
<td>No change between pre-test and post-test.</td>
<td>10MWT (p &lt; 0.01)</td>
</tr>
<tr>
<td>Self-selected walking speed</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Walking capacity</td>
<td>Clinically important change between pre-test and post-test.</td>
<td>Minimally clinically important change between pre-test and post-test.</td>
<td>No change between pre-test and post-test.</td>
<td>6MWT (p &lt; 0.01)</td>
</tr>
<tr>
<td>Participants’ perception of change in walking ability: GRoC</td>
<td>Most GRoC scores between +5 to +7.</td>
<td>Most GRoC scores between +3 to +4.</td>
<td>Most GRoC scores are &lt; 3.</td>
<td>75% scored ≥ 5 Green</td>
</tr>
</tbody>
</table>

Note. AEs = adverse events; BST = ballistic strength training; 6MWT = 6-minute walk test; 10MWT = 10-metre walk test; GRoC = global rating of change scale.
weight, potentially making them easier to perform accurately. In our study, not all of the participants were able to achieve the desired skills, which is possibly due to not having enough time to perfect the exercises prior to discharge. It is likely that continuing with these exercises after discharge may further aid in the rehabilitation process. BST exercises, without the need for specialised equipment, could be explored as an option for continued rehabilitation in the community, which could also improve the generalisability of the intervention (Williams & Ada, 2022).

All participants were able to achieve normal comfortable walking speeds for people aged 20 to 69 years of age of between 1.2 m/s and 1.55 m/s (Bohannon & Andrews, 2011). Walking speed, also called the sixth vital sign (Fritz & Lusardi, 2009), is associated with community walking ability (Andrews et al., 2010). Walking efficiency is directly related to the energy cost of walking. Gait impairments may increase energy expenditure, leading to fatigue and affecting walking capacity (Awad et al., 2015; Bae et al., 2018). We used both the 10mWT and the 6MWT to provide a comprehensive picture of walking ability. Both walking speed and distance were markedly improved following the BST intervention, indicating that the selection of outcome measures was appropriate.

Additionally, participants perceived that their walking ability had improved, validating the objectively measured walking speed and walking endurance. One participant struggled to compare pre-test and post-test performance using the GRoC scale due to short-term memory difficulties caused by the TBI. External compensatory strategies such as video feedback or participant diaries may mitigate short-term memory and self-awareness difficulties (Nowell et al., 2020; Schmidt et al., 2013).

Our findings are limited by the small sample size and by being conducted at a single rehabilitation centre. Also, due to the study design, the secondary outcomes cannot be fully attributed to BST. The results on the treatment effect should thus be interpreted with caution, as our study was not powered for secondary outcomes (Cordner et al., 2020).

Our results contribute to research and clinical practice. This feasibility study lays the foundation for future larger definitive trials testing the BST intervention (Harvey, 2018; Orsmond & Cohn, 2015). Our results support the current literature on the safety and feasibility of BST training in neurological conditions (Cordner et al., 2020). This feasibility study, to our knowledge, is the first to evaluate BST intervention in the early inpatient rehabilitation phase, diversifying the inpatient intervention toolbox for clinicians treating ambulatory individuals with TBI.

To verify the efficacy of BST intervention in individuals with TBI in an inpatient rehabilitation centre, it is proposed that the intervention is compared with a dose-matched control in a randomised controlled trial (RCT) with a large, adequately powered sample size. All objectives, except for recruitment capability (due to unforeseen circumstances), point towards proceeding with a full-scale trial. Future trials might want to consider a multi-centre study design. We also recommend a follow-up time point to examine the lasting effects of the intervention, which could include the effects of the BST on quality of life.

**CONCLUSION**

This feasibility study indicates that BST could be used in a regular inpatient rehabilitation programme on ambulatory adults within 6 months following moderate to severe TBI. Although preliminary, our results suggest that BST may assist in improving walking outcomes. This study further highlights the saliency of BST as a therapeutic tool in neurorehabilitation. Our results support an RCT to explore the efficacy of BST on the function and quality of life of individuals with TBI.

**KEY POINTS**

1. BST is a feasible and promising rehabilitation method to improve the walking outcomes of individuals with moderate to severe TBI in an inpatient rehabilitation setting.
2. Larger clinical trials are warranted to assess the efficacy of BST in this population group.

**DISCLOSURES**

The research project received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors. The authors report no conflicts of interest that may be perceived to interfere with or bias this study. The author(s) disclose receipt of equipment sponsorship for a Total Gym Jump Trainer from HQH Fitness. The equipment sponsor had no role in the study design, data collection, analysis, interpretation, writing of the manuscript, or decision to submit for publication.
PERMISSIONS
The trial was approved by the New Zealand Health and Disability Ethics Committee (reference 21/CEN/238) and the institutional Faculty of Health Sciences Research Ethics Committee (reference 399/2021).

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CONTRIBUTIONS OF AUTHORS
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ADDRESS FOR CORRESPONDENCE
Izel Gillifan, Department of Physiotherapy, School of Healthcare Sciences, Faculty of Health Sciences, University of Pretoria, Pretoria, 0031, South Africa.

Email: u10128523@tuks.co.za

REFERENCES


Appendix A

INTERVENTION: BALLISTIC STRENGTH TRAINING EXERCISE PROGRAMME

Prescription protocol

- **Frequency**: 2 sessions per week.
- **Duration**: approximately 30 min each.
- **Time**: maximum of 4 weeks (8 sessions), dependent upon date of discharge from the rehabilitation centre.
- **Level of intensity**:
  - Similar to a recent protocol for a post-stroke population (Hendrey et al., 2018), the level of intensity is set to the maximum level the participant can manage while maintaining the correct lower limb alignment, using the correct technique and desired range of motion.

- **Dosage**:
  - The exercise programme is divided into two parts, each consisting of four exercises. Part A is completed on a reclined jump trainer (below body weight) and part B uses body weight with or without upper limb support and resistance. There is a 2 min rest break between each part.
  - Each exercise is performed for 2 min (timed by stopwatch).
  - Rest breaks are allowed as required throughout each exercise, being participant or therapist initiated. The participant is encouraged to complete as many repetitions as possible during each exercise, with emphasis on the quality of movement.
  - Recovery time of at least 48 hr between each ballistic exercise session.

- **Progression principles** (similar to those of Hendrey et al., 2018):
  - First, the aim is to ensure the correct movement pattern is achieved.
  - Second, the speed of movement is increased as a progression once the correct movement pattern is achieved. A metronome provides auditory feedback, with a target speed of 60 beats per min for five of the exercises.
  - Third, increased loads are added as a progression (either by increasing the amount of body weight by increasing the incline or adding external resistance) without altering speed and quality of movement. For exercises in part A (using the jump trainer), resistance is increased by increasing the incline of the leg sled by one increment as marked on the machine (ranging between 30% of body weight at level 1 and 65% of body weight at level 7, using the physiotherapy setting) at a time. Once the maximum incline is achieved (65% of body weight), additional resistance is added using the resistance bands on the jump trainer itself if necessary. Additional resistance of up to 31.75 kg is available through resistance bands integrated within the machine. For exercises in part B (body weight or more), resistance is gradually added by using TheraBand, ankle weights, or a weight-stack pulley system.

- **Motivational or prompting strategies**:
  - A metronome set at 60 beats per min is used as an auditory prompt to guide the target speed of movement for exercises 2, 3, 5, 6, and 7.
  - A printed and laminated jump height metre provides a visual prompt, combined with verbal feedback on the jump height achieved (every 5 cm represents a different colour, as measured on the jump trainer) for exercises 1 and 4.
  - A moveable yellow line is marked on the floor to mark the longest distance achieved during the bounding exercise (exercise 8).

- **Exercise log**:
  - Each participant has an exercise log to record the attendance, amount of assistance, load, and any reported adverse effects.
  - Use of orthosis (such as knee range of motion brace to prevent knee hyperextension, which allows free knee flexion) or therapist hands-on stabilisation is permitted.

Exercises – Part A

**Exercise 1: Double leg jump squats**

- **Instructions**: Go down into a squat and jump as high as you can pushing through your toes (Figure A1).
- **Target**: Jump height.

![Double Leg Jump Squats on Jump Trainer](image)
**Exercise 2: Bilateral calf-raises**
- Instructions: Rise up onto your toes keeping your knees straight, then lower back down. Rise back up as quickly as you can (Figure A2).
- Target: Movement speed of 60 beats per min.

**Figure A2**
*Bilateral Calf Raises on Jump Trainer*

**Exercise 3: Double leg extension jumps**
- Instructions: Hop on the spot pushing through your toes, while keeping your knees straight. Hop as quickly as possible (Figure A3).
- Target: Movement speed of 60 beats per min.

**Figure A3**
*Double Leg Extension Jumps on Jump Trainer*

**Exercise 4: Staggered jump squat**
- Instructions: Place one foot higher than the other. Go down into a squat and jump as high as you can – alternate your foot position with every jump (Figure A4).
- Target: Jump height.

**Figure A4**
*Staggered Jump Squat on Jump Trainer*

**Exercises – Part B**

**Exercise 5: Alternate knee release on mini-trampoline**
- Instructions: Bend one knee while keeping the other knee straight and alternate between the two. Your toes should remain in contact with the mini-trampoline at all times. Try to alternate raising each heel as quickly as possible keeping your knees soft (Figure A5).
- Target: Movement speed of 60 beats per min.

**Figure A5**
*Alternate Knee Release on Mini-trampoline*
Exercise 6: Scissor jumps on mini-trampoline
• Instructions: Alternate your feet as quickly as possible pushing through your toes, while keeping your knees straight (Figure A6).
• Target: Movement speed of 60 beats per min.

Figure A6
Scissor Jumps on Mini-trampoline

Exercise 7: Hip and knee flexion from extension (affected and less affected leg)
• Instructions: Stand with one leg extended behind you. Keeping hips and back still, bend your hip and knee up as quickly as possible. Switch legs after 1 min (Figure A7).
• Target: Movement speed of 60 beats per min.

Figure A7
Hip and Knee Flexion from Extension

Exercise 8: Bounding (step descent with affected and less affected leg)
• Instructions: Push through one leg and jump as far as you can, coming to land on your other leg. Use the rail for balance if needed, but don’t pull on it. Switch legs after 1 min (Figure A8).
• Target: Bounding distance.

Figure A8
Bounding From a Step