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

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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.

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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., 2019; 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 ACTRN12621000107389).

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 and interrater reliability (Tyson & Connell, 2009; van Loo et al., 2003). Participants walked along a 14 m track, and we recorded the time taken to walk the middle 10 m at a comfortable pace. The average speed was calculated from two trials. We 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. The study used a minimally important clinical difference of 34.4 m for the stroke population (Tang et al., 2012). 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., 2009). The GRoC scale ranges from negative seven (a very 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

Figure 1

CONSORT Flow Diagram Representing the Flow of Participants

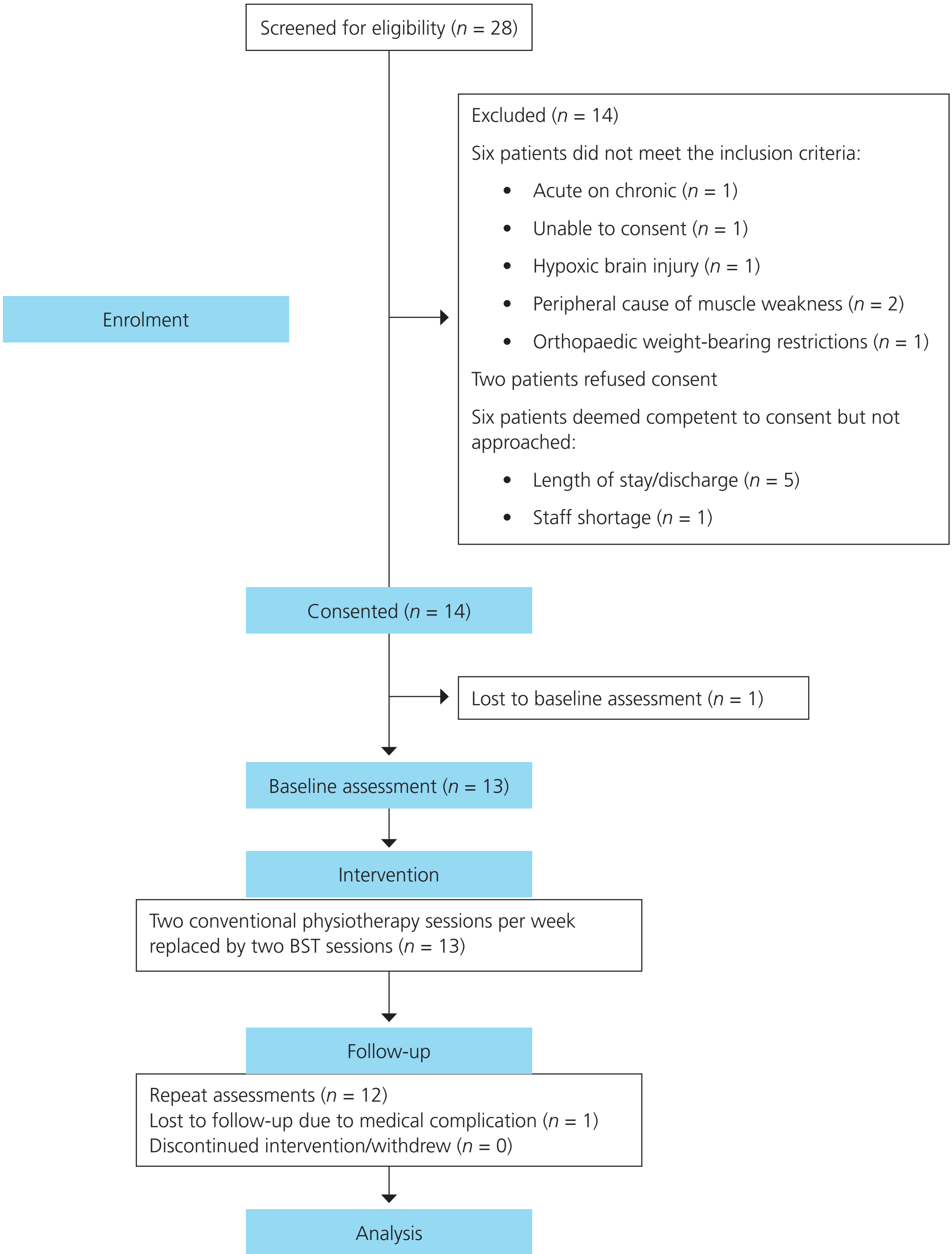


Table 1

*Demographic Characteristics of Ballistic Strength Training Study Participants with Traumatic Brain Injury (*N *= 14)*

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

Note. PTA = post-traumatic amnesia; TBI = traumatic brain injury.
[a] Unless otherwise indicated.

Table 2

*Participant Pre-test–Post-test Walking Parameters (*N *= 12)*

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

Note: 10MWT = 10-metre walk test; FIM = functional independence measure.

perceived a positive change in walking ability (GRoC, *M* = +5, *SD* = 1). The traffic light stop-go criteria were green for the effects of BST on walking outcomes. Table 3 provides a visual representation of the results according to the traffic light progression criteria.

DISCUSSION

In this study, we investigated the feasibility of implementing BST to improve the walking outcomes of individuals with moderate to severe TBI in an inpatient setting. We found that BST combined with usual care is safe and feasible when delivered in a cohort of individuals with TBI. The traffic light stop-go criteria indicated that it would be feasible to scale up this study to a larger trial but that future studies should consider modification of the recruitment process to improve enrolment.

In our study, recruitment capability was influenced by various factors. The number of participants that could be recruited was limited by the short recruitment period of 6 months. Once an eligible individual was able to provide informed consent, the remaining length of stay was often too short to allow for participation in the study. The proportion of eligible participants was further affected by the COVID-19 pandemic, which affected admissions and discharges from the rehabilitation centre, as well as staff availability.

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 our study, participants did not experience any AEs, suggesting that BST is safe for individuals in early recovery from TBI. Although not tested, therapist supervision and hands-on assistance likely contributed to the safety of the intervention. One participant reported mild abdominal discomfort unrelated 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 strength training in people with neurological conditions (Cordner et al., 2020; Taylor et al., 2005).

In our study, participants positively accepted the intervention, showing that a challenging intervention such as BST is suitable alongside usual care to promote early neuroplasticity 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 3

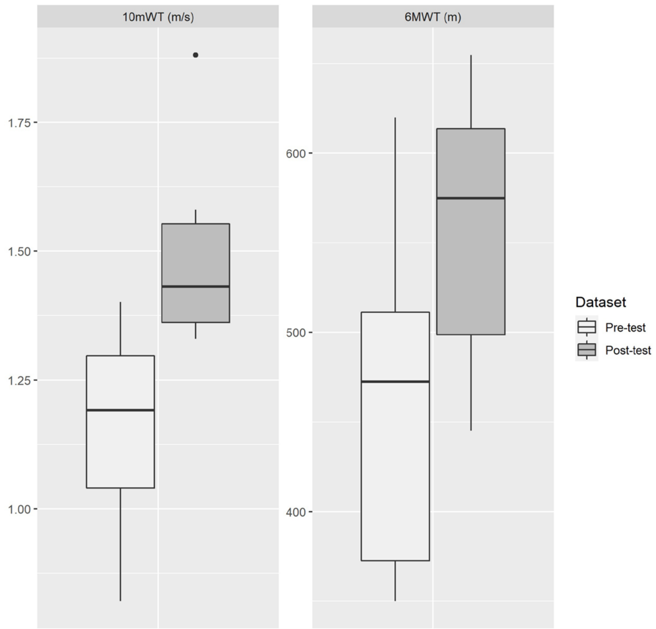
Traffic Light Progression Criteria Used to Decide if the Ballistic Strength Training Feasibility Trial Could Be Up-Scaled to a Full-size Trial

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

Note. AEs = adverse events; BST = ballistic strength training; 6MWT = 6-minute walk test; 10MWT = 10-metre walk test; GRoC = global rating of change scale.

Figure 2

Boxplots Comparing Pre-test–post-test Values for the 10-metre Walk Test (10mWT, in m/s) and 6-minute Walk Test (6MWT, in m) (N = 12).



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

Conceptualisation and methodology, IG; Statistical analysis (with statistical support), IG and AvH; Writing – manuscript drafting and original draft preparation, IG; Writing – review and editing, IG, DJM, and AvH: Supervision, DJM and AvH.

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REFERENCES

Andrews, A. W., Chinworth, S. A., Bourassa, M., Garvin, M., Benton, D., & Tanner, S. (2010). Update on distance and velocity requirements for community ambulation. *Journal of Geriatric Physical Therapy*, *33*(3), 128–134.

Archer, T., Svensson, K., & Alricsson, M. (2012). Physical exercise ameliorates deficits induced by traumatic brain injury. *Acta Neurologica Scandinavica*, *125*(5), 293–302. https://doi.org/10.1111/j.1600-0404.2011.01638.x

Awad, L. N., Palmer, J. A., Pohlig, R. T., Binder-Macleod, S. A., & Reisman, D. S. (2015). Walking speed and step length asymmetry modify the energy cost of walking after stroke. *Neurorehabilitation and Neural Repair*, *29*(5), 416–423. https://doi.org/10.1177/1545968314552528

Bae, J., Awad, L. N., Long, A., O'Donnell, K., Hendron, K., Holt, K. G., Ellis, T. D., & Walsh, C. J. (2018). Biomechanical mechanisms underlying exosuit-induced improvements in walking economy after stroke. *Journal of Experimental Biology*, *221*(5), jeb168815. https://doi.org/10.1242/jeb.168815

Bohannon, R. W., & Andrews, A. W. (2011). Normal walking speed: A descriptive meta-analysis. *Physiotherapy*, *97*(3), 182–189. https://doi.org/10.1016/j.physio.2010.12.004

Campbell, K. G., Batt, M. E., & Drummond, A. (2020). A feasibility study of the physiotherapy management of urinary incontinence in athletic women: Trial protocol for the POsITIve study. *Pilot and Feasibility Studies*, *6,* 103. https://doi.org/10.1186/s40814-020-00638-6

Charrette, A. L., Lorenz, L. S., Fong, J., O'Neil-Pirozzi, T. M., Lamson, K., Demore-Taber, M., & Lilley, R. (2016). Pilot study of intensive exercise on endurance, advanced mobility and gait speed in adults with chronic severe acquired brain injury. *Brain Injury*, *30*(10), 1213–1219. https://doi.org/10.1080/02699052.2016.1187766

Cordner, T., Egerton, T., Schubert, K., Wijesinghe, T., & Williams, G. (2020). Ballistic resistance training: Feasibility, safety, and effectiveness for improving mobility in adults with neurologic conditions: A systematic review. *Archives of Physical Medicine and Rehabilitation*, *102*(4), 735–751. https://doi.org/10.1016/j.apmr.2020.06.023

Dorsch, S., Ada, L., & Alloggia, D. (2018). Progressive resistance training increases strength after stroke but this may not carry over to activity: A systematic review. *Journal of Physiotherapy*, *64*(2), 84–90. https://doi.org/10.1016/j.jphys.2018.02.012

Eldridge S. M., Chan C. L., Campbell M. J., Bond C. M., Hopewell S., Thabane L., Lancaster G. A., & the PAFS consensus group (2016). CONSORT 2010 statement: Extension to randomised pilot and feasibility trials. *BMJ*, *355*, i5239. https://doi.org/10.1136/bmj.i5239

Fritz, S., & Lusardi, M. (2009). White paper: "Walking speed: The sixth vital sign". *Journal of Geriatric Physical Therapy*, *32*(2), 46–49. https://doi.org/10.1519/00139143-200932020-00002

Fulk, G. D., Ludwig, M., Dunning, K., Golden, S., Boyne, P., & West, T. (2011). Estimating clinically important change in gait speed in people with stroke undergoing outpatient rehabilitation. *Journal of Neurologic Physical Therapy*, *35*(2), 82–89. https://doi.org/10.1097/npt.0b013e318218e2f2

Gilfillan, I., Mothabeng, D. J., & van Heerden, A. (2023). Feasibility of ballistic strength training to improve mobility of inpatients with traumatic brain injury: A study protocol. *New Zealand Journal of Physiotherapy*, *51*(1), S1–S8. https://doi.org/10.15619/NZJP/51.1.08

Harvey, L. (2018). Feasibility and pilot studies pave the way for definitive trials. *Spinal Cord*, *56*(8), 723–724. https://doi.org/10.1038/s41393-018-0184-x

Hendrey, G., Clark, R. A., Holland, A. E., Mentiplay, B. F., Davis, C., Windfeld-Lund, C., Raymond, M. J., & Williams, G. (2018). Feasibility of ballistic strength training in subacute stroke: A randomized, controlled, assessor-blinded pilot study. *Archives of Physical Medicine and Rehabilitation*, *99*(12), 2430–2446. https://doi.org/10.1016/j.apmr.2018.04.032

Hornby, T. G., Reisman, D. S., Ward, I. G., Scheets, P. L., Miller, A., Haddad, D., Fox, E. J., Fritz, N. E., Hawkins, K., Henderson, C. E., Hendron, K. L., Holleran, C. L., Lynskey, J. E., Walter, A., & and the Locomotor CPG Appraisal Team (2020). Clinical practice guideline to improve locomotor function following chronic stroke, incomplete spinal cord injury, and brain injury. *Journal of Neurologic Physical Therapy*, *44*(1), 49–100. https://doi.org/10.1097/NPT.0000000000000303

Kamper, S. J., Maher, C. G., & Mackay, G. (2009). Global rating of change scales: A review of strengths and weaknesses and considerations for design. *Journal of Manual & Manipulative Therapy*, *17*(3), 163–170. https://doi.org/10.1179/jmt.2009.17.3.163

Katz, D. I., White, D. K., Alexander, M. P., & Klein, R. B. (2004). Recovery of ambulation after traumatic brain injury. *Archives of Physical Medicine and Rehabilitation*, *85*(6), 865–869. https://doi.org/10.1016/j.apmr.2003.11.020

Kleim, J. A., & Jones, T. A. (2008). Principles of experience-dependent neural plasticity: Implications for rehabilitation after brain damage. *Journal of Speech, Language, and Hearing Research*, *51*(1), S225–S239. https://doi.org/10.1044/1092-4388(2008/018)

Lamontagne, M. E., Perreault, K., & Gagnon, M. P. (2014). Evaluation of the acceptability, feasibility and effectiveness of two methods of involving patients with disability in developing clinical guidelines: Study protocol of a randomized pragmatic pilot trial. *Trials*, *15*, 118. https://doi.org/10.1186/1745-6215-15-118

McFadyen, B. J., Swaine, B., Dumas, D., & Durand, A. (2003). Residual effects of a traumatic brain injury on locomotor capacity: A first study of spatiotemporal patterns during unobstructed and obstructed walking. *Journal of Head Trauma Rehabilitation*, *18*(6), 512–525. https://doi.org/10.1097/00001199-200311000-00005

Mossberg, K. A. (2003). Reliability of a timed walk test in persons with acquired brain injury. *American Journal of Physical Medicine & Rehabilitation*, *82*(5), 385–390. https://doi.org/10.1097/01.phm.0000052589.96202.be

Nadeau, S., Gravel, D., Arsenault, A. B., & Bourbonnais, D. (1999). Plantarflexor weakness as a limiting factor of gait speed in stroke subjects and the compensating role of hip flexors. *Clinical Biomechanics*, *14*(2), 125–135. https://doi.org/10.1016/s0268-0033(98)00062-x

National Cancer Institute. (2017). *Common terminology criteria for adverse events (CTCAE)* (Version 5.0). U. S. Department of Health Human Services, National Institutes of Health. https://ctep.cancer.gov/protocoldevelopment/electronic_applications/docs/ctcae_v5_quick_reference_8.5x11.pdf

New Zealand Guidelines Group. (2006). *Traumatic brain injury: Diagnosis, acute management and rehabilitation* [Evidence-based best practice guideline]. Accident Compensation Cooperation. https://www.moh.govt.nz/notebook/nbbooks.nsf/0/B8738C3605889A6ACC257A6D00809243/$file/traumatic-brain-injury-acc.pdf

Nowell, C., Downing, M., Bragge, P., & Ponsford, J. (2020). Current practice of cognitive rehabilitation following traumatic brain injury: An international survey. *Neuropsychological Rehabilitation*, *30*(10), 1976–1995. https://doi.org/10.1080/09602011.2019.1623823

Orsmond, G. I., & Cohn, E. S. (2015). The distinctive features of a feasibility study: Objectives and guiding questions. *Occupational Therapy Journal of Research*, *35*(3), 169–177. https://doi.org/10.1177/1539449215578649

Peters, D. M., Jain, S., Liuzzo, D. M., Middleton, A., Greene, J., Blanck, E., Sun, S., Raman, R., & Fritz, S. L. (2014). Individuals with chronic traumatic brain injury improve walking speed and mobility with intensive mobility training. *Archives of Physical Medicine and Rehabilitation*, *95*(8), 1454–1460. https://doi.org/10.1016/j.apmr.2014.04.006

R Core Team. (2018). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org/

Schmidt, J., Fleming, J., Ownsworth, T., & Lannin, N. A. (2013). Video feedback on functional task performance improves self-awareness after traumatic brain injury: A randomized controlled trial. *Neurorehabilitation and Neural Repair*, *27*(4), 316–324. https://doi.org/10.1177/1545968312469838

Tang, A., Eng, J. J., & Rand, D. (2012). Relationship between perceived and measured changes in walking after stroke. *Journal of Neurologic Physical Therapy*, *36*(3), 115–121. https://doi.org/10.1097/NPT.0b013e318262dbd0

Taylor, N. F., Dodd, K. J., & Damiano, D. L. (2005). Progressive resistance exercise in physical therapy: A summary of systematic reviews. *Physical Therapy*, *85*(11), 1208–1223. https://doi.org/10.1093/ptj/85.11.1208

Tverdal, C. B., Howe, E. I., Røe, C., Helseth, E., Lu, J., Tenovuo, O., & Andelic, N. (2018). Traumatic brain injury: Patient experience and satisfaction with discharge from trauma hospital. *Journal of Rehabilitation Medicine*, *50*(6), 505–513. https://doi.org/10.2340/16501977-2332

Tyson, S., & Connell, L. (2009). The psychometric properties and clinical utility of measures of walking and mobility in neurological conditions: A systematic review. *Clinical Rehabilitation*, *23*(11), 1018–1033. https://doi.org/10.1177/0269215509339004

van Loo, M. A., Moseley, A. M., Bosman, J. M., de Bie, R. A., & Hassett, L. (2003). Inter-rater reliability and concurrent validity of walking speed measurement after traumatic brain injury. *Clinical Rehabilitation*, *17*(7), 775–779. https://doi.org/10.1191/0269215503cr677oa

van Loo, M. A., Moseley, A. M., Bosman, J. M., de Bie, R. A., & Hassett, L. (2004). Test-re-test reliability of walking speed, step length and step width measurement after traumatic brain injury: A pilot study. *Brain Injury*, *18*(10), 1041–1048. https://doi.org/10.1080/02699050410001672314

Van Vulpen, L. F., De Groot, S., Rameckers, E., Becher, J. G., & Dallmeijer, A. J. (2017). Improved walking capacity and muscle strength after functional power-training in young children with cerebral palsy. *Neurorehabilitation and Neural Repair*, *31*(9), 827–841. https://doi.org/10.1177/1545968317723750

Vella, M. A., Crandall, M. L., & Patel, M. B. (2017). Acute management of traumatic brain injury. *Surgical Clinics*, *97*(5), 1015–1030. https://doi.org/10.1016/j.suc.2017.06.003

Walker, W. C., & Pickett, T. C. (2007). Motor impairment after severe traumatic brain injury: A longitudinal multicenter study. *Journal of Rehabilitation Research and Development*, *44*(7), 975–982.

Williams, G., & Ada, L. (2022). The safety and accuracy of home-based ballistic resistance training for people with neurological conditions. *Physiotherapy Theory and Practice*. Advance online publication. https://doi.org/10.1080/09593985.2022.2059422

Williams, G., Clark, R. A., Hansson, J., & Paterson, K. (2014). Feasibility of ballistic strengthening exercises in neurologic rehabilitation. *American Journal of Physical Medicine & Rehabilitation*, *93*(9), 828–833. https://doi.org/10.1097/phm.0000000000000139

Williams, G., Hassett, L., Clark, R., Bryant, A., Olver, J., Morris, M. E., & Ada, L. (2019). Improving walking ability in people with neurologic conditions: A theoretical framework for biomechanics-driven exercise prescription. *Archives of Physical Medicine and Rehabilitation*, *100*(6), 1184–1190. https://doi.org/10.1016/j.apmr.2019.01.003

Williams, G., Kahn, M., & Randall, A. (2014). Strength training for walking in neurologic rehabilitation is not task specific: A focused review. *American Journal of Physical Medicine & Rehabilitation*, *93*(6), 511–522. https://doi.org/10.1097/phm.0000000000000058

Williams, G., Morris, M. E., Schache, A., & McCrory, P. R. (2009). Incidence of gait abnormalities after traumatic brain injury. *Archives of Physical Medicine and Rehabilitation*, *90*(4), 587–593. https://doi.org/10.1016/j.apmr.2008.10.013

Williams, G., & Willmott, C. (2012). Higher levels of mobility are associated with greater societal participation and better quality-of-life. *Brain Injury*, *26*(9), 1065–1071. https://doi.org/10.3109/02699052.2012.667586

Williams, G. P., & Schache, A. G. (2010). Evaluation of a conceptual framework for retraining high-level mobility following traumatic brain injury: Two case reports. *Journal of Head Trauma Rehabilitation*, *25*(3), 164–172. https://doi.org/10.1097/htr.0b013e3181dc120b

Williams, G. P., Schache, A. G., & Morris, M. E. (2013). Mobility after traumatic brain injury: Relationships with ankle joint power generation and motor skill level. *Journal of Head Trauma Rehabilitation*, *28*(5), 371–378. https://doi.org/10.1097/HTR.0b013e31824a1d40

Wilson, T., Martins, O., Efrosman, M., DiSabatino, V., Benbrahim, B. M., & Patterson, K. K. (2019). Physiotherapy practice patterns in gait rehabilitation for adults with acquired brain injury. *Brain Injury*, *33*(3), 333–348. https://doi.org/10.1080/02699052.2018.1553067

Zhu, X. L., Poon, W. S., Chan, C. C., & Chan, S. S. (2007). Does intensive rehabilitation improve the functional outcome of patients with traumatic brain injury (TBI)? A randomized controlled trial. *Brain Injury*, *21*(7), 681–690. https://doi.org/10.1080/02699050701468941

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.

Figure A1

Double Leg Jump Squats on Jump Trainer

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