A block randomised controlled trial investigating changes in postural control following a personalised 12-week exercise programme for individuals with lower limb amputation

Zoe A. Schafer, PhD[1] and Natalie Vanicek, PhD[1]

[1]Department of Sport, Health and Exercise Science, University of Hull, Hull, HU6 7RX, United Kingdom

Corresponding author

Prof Natalie Vanicek, Department of Sport, Health and Exercise Science, University of Hull, Hull, HU6 7RX, United Kingdom. Tel: +44 (0)1482 463607 email: n.vanicek@hull.ac.uk

Acknowledgements

Funding for this study was provided by the British Association of Chartered Physiotherapists in Amputee Rehabilitation (BACPAR), and Help for Health in the East Riding of Yorkshire.

Conflict of Interest statement

The authors declare that there are no conflicts of interest.

Clinical Trials Registration Number: ISRCTN30210699 (ISRCTN Registry)

Highlights

- This exercise programme improved aspects of postural control in lower limb amputees
- Exercise reduced reliance on visual input and/or enhanced somatosensory interpretation
- A lack of exercise training increased weight-bearing asymmetry during perturbations
- Self-reported changes in balance confidence were not identified

A block randomised controlled trial investigating changes in postural control following a personalised 12-week exercise programme for individuals with lower limb amputation

Abstract (current word count: 298)

Background: Individuals with a lower limb amputation (LLA) have an increased risk of falls and often report lower balance confidence. They must compensate for altered mechanics and prosthetic limitations in order to execute appropriate motor responses to postural perturbations. Personalised exercise could be an effective strategy to enhance balance and reduce falls.

Research question: In this study, we investigated whether a personalised exercise programme could improve postural control and self-reported balance confidence in individuals with an LLA.

Methods: Participants were block randomised into two groups (exercise, n=7; control, n=7) based on age and level of amputation. The exercise group completed a 12-week personalised exercise programme, including home-based exercise sessions, consisting of balance, endurance, strength, and flexibility training. The control group continued with their normal daily activities. All participants performed the Sensory Organization Test (SOT) and Motor Control Test (MCT) on the NeuroCom SMART Equitest, and completed the Activities-specific Balance Confidence-UK (ABC) self-report questionnaire, at baseline and post-intervention.

Results and significance: Exercise group equilibrium scores improved significantly when standing on an unstable support surface with no visual input and inaccurate somatosensory feedback (SOT condition 5, P<0.012, d=1.45). There were significant group*time interactions for medium (P=0.029) and large (P=0.048) support surface forward translations, which were associated with a trend towards increased weight-bearing on the intact limb in the control group (medium: P=0.055; large: P=0.087). No significant changes in ABC score were observed. These results indicate reduced reliance on visual input, and/or enhanced interpretation of somatosensory input, following an exercise programme. However, objective improvements in aspects of postural control were not associated with subjective improvements in self-reported balance confidence. More weight-bearing asymmetry in the control group suggests that a lack of targeted exercise training may have detrimental effects, with potential adverse long-term musculoskeletal consequences, that were quantifiable within a short timeframe.

Key words postural control; balance confidence; lower limb amputation; exercise; NeuroCom

Abbreviations

ABC: Activities-specific Balance Confidence questionnaire

CDP: computerised digital posturography

LLA: Lower limb amputation

LoB: loss of balance

MCT: Motor Control Test

SOT: Sensory Organization Test

Introduction

Effective postural control requires the integration of proprioceptive, somatosensory, vestibular and visual afferent signals into the central nervous system, with the appropriate selection and execution of motor responses during static equilibrium or after a postural disturbance[1, 2]. Following a lower limb amputation (LLA), the postural control system must adjust to the loss of proprioceptive and somatosensory information from the amputated limb, and from altered weight-bearing symmetry, joint stiffness and limitations with the prosthesis[3-7].These factors impair normal reflex and postural control strategies[8, 9] and may adversely affect the successful execution of appropriate responses[10], especially in more challenging environments.

Passive prosthetic ankle-feet are unable to generate an active ankle strategy; thus, alternative strategies, such as the hip, combined hip and ankle (utilising the intact ankle), or stepping strategies, are used to maintain effective postural control[5, 11]. Increased postural sway, exaggerated centre of pressure responses, and greater reliance on visual feedback have all been reported during static and/or dynamic standing balance for individuals with an LLA[5, 8, 12-14]. Moreover, reliance on visual feedback is significantly greater in those with a history of falls compared with non-fallers[11]. Delayed postural responses have also been reported following perturbations[11, 15] and may prove ineffective in challenging or unpredictable environments. Thus, it is not surprising that individuals with an LLA are at an increased risk of falls and recurrent falls[16, 17].

People with an LLA fall for a number of different reasons including disruptions to the base of support and intrinsic destabilising factors, as well as slips, trips and inadequate shifting of weight[17]. Despite the high incidence of falls in this population, few studies have investigated the effects of exercise interventions for enhanced postural control in people who have an LLA. This is surprising given that there are many studies that have demonstrated the positive effects of exercise training on static and dynamic postural control in older, able-bodied individuals[18-22]. Some targeted interventions, such as perturbation training specifically for individuals with a transtibial amputation, have shown encouraging results for better postural control[23, 24]. Another study delivered a short, six-week exercise programme and reported significantly increased Activities-specific Balance Confidence questionnaire (ABC) scores in a heterogeneous group of individuals with an LLA[25]. As such, exercise training may be a suitable intervention to improve postural control and balance confidence during daily activities after limb loss. However, to the best of the authors' knowledge, no other studies have investigated the effects of a personalised exercise intervention on postural control, delivered over a longer time, and quantified objectively with computerised dynamic posturography (CDP) following an LLA.

The aim of this block randomised controlled trial was to evaluate the effectiveness of a 12-week personalised exercise programme on postural control for individuals with an LLA during different balancing conditions when the somatosensory, visual and vestibular systems were challenged. We also evaluated whether an exercise programme would change self-reported balance confidence. It was hypothesised that participants in the exercise group would demonstrate improved (higher) equilibrium and strategy scores, and sensory ratios, and better weight symmetry during stable and unstable balance conditions, as measured by the NeuroCom SMART Equitest, and increased ABC scores.

Methods

This study received ethical approval from the local NHS Research Ethics Committee (reference: 14/YH/1138). Participants gave written informed consent prior to study enrolment.

Participants

Individuals with an LLA were recruited from their local prosthetics services centre between July 2015 and June 2016 if they met the following inclusion criteria: they had a unilateral transtibial or transfemoral amputation, of any aetiology; had reported a fall in the previous two years or were deemed at high risk of falling by their healthcare team; wore their prosthesis daily; and could walk independently along level surfaces, with or without mobility aids. Participants were excluded if they had any cardiac complications; severe infections; uncontrolled hypertension, asthma or diabetes; cognitive disorders; non-lifestyle chronic diseases; current musculoskeletal injury including severe lower back pain; severe osteoporosis; or if they were already involved in a structured exercise programme. Participants should have been prepared to commit to the required time involved in the study and, with best intentions, planned to attend the supervised exercise sessions twice weekly throughout the duration of the programme, in addition to the baseline and follow-up assessments. Participants were established prosthesis users and had completed a prosthetics rehabilitation programme previously. Broad inclusion criteria were applied to enrol a heterogeneous group of participants, reflective of what a real-world exercise group would resemble in the community. Participants were recruited from the local area and thus represent a sample of convenience. Four hundred potentially eligible patients were screened from the local prosthetics centre database and were assessed for eligibility: 385 individuals were ineligible or declined to take part and 14 were analysed after one person randomised (to the control group) declined to take part in postural control testing. Participants were block randomised into two groups based on age and level of amputation (exercise, n=7; control, n=7), following baseline assessments (Table 1).

Exercise intervention

Participants in the exercise group undertook a 12-week supported exercise intervention by attending a twice-weekly supervised group exercise session (performed in circuit-style) at the University, and completing personalised exercises at home once-weekly, progressing to twice-weekly, after six weeks. The exercise programme was novel because it is uncommon for exercise to be delivered uniquely to a group of prosthesis users outside of the NHS. Exercises were personalised based on findings from each participant's baseline data, which included gait biomechanics, strength and postural control profiles, their exercise goals, as well as level of amputation and prosthetic constraints. The programme involved multiple components and incorporated exercises targeting muscle strength, balance, gait endurance, flexibility, and cardiovascular fitness. Specifically, exercises included concentric and eccentric strengthening of key muscle groups (plantarflexors, knee extensors, hip extensors, flexors, abductors and adductors, and abdominal muscles) and dynamic balance (including picking up objects from the floor and balancing on a compliant surface). Group and home-based exercise sessions were also personalised according to amount of resistance, body positioning (e.g., in respect to movement with or against gravity, or seated versus standing), and individually graded according to progression. A more detailed description of the exercise programme has been published previously[26].

Participants in the control group did not engage in any structured exercise programme and maintained their normal activities of daily living. They were asked to refrain from initiating any new exercise regimens during the study period.

Data collection

Participants completed the NeuroCom assessments at two time points: baseline and post-intervention. Postural responses to dynamic perturbations were measured using the NeuroCom SMART Equitest[a], during the Sensory Organization Test (SOT) and Motor Control Test (MCT), both of which have had their reliability and/or validity assessed in populations of older adults and with an LLA[27, 28]. Moreover, changes in weight-bearing symmetry and balance in individuals with an LLA have been evaluated previously with the NeuroCom[29, 30]. The use of the NeuroCom system provided objective measurements of postural control, able to detect and quantify subtle changes in weight-bearing symmetry, response latencies and postural control strategies. As the intervention included exercises that challenged the sensory systems responsible for balance (e.g., standing on a compliant surface, twisting from side to side, bending down to floor level) and weight distribution (e.g., rhythmic weight-shifting), we believed the SOT and MCT tests were appropriate tests to quantify the effects of our exercise intervention on postural control.

The SMART Equitest[a] hardware system incorporates a dual-force plate system capable of graded backwards and forwards translations and sagittal plane rotation about the ankle joint. Four transducers under the force plate measured vertical forces for each foot individually; a fifth transducer measured shear force. The force sampling frequency was 100Hz. The sway-referenced visual surround rotated forwards and backwards, up to a maximum velocity of 15°/s.

Participants' heights were entered into the NeuroCom software[a] allowing support surface translations to be scaled according to height for the MCT. All participants wore a safety harness to prevent an actual fall. The harness allowed postural sway beyond normal limits of stability (4° posteriorly, 8.5° anteriorly, and 6° laterally)[31]. Wearing flat shoes, each foot was positioned on one force plate such that the medial malleoli were aligned with the axis of rotation of the support surface, according to the manufacturer's instructions. The prosthesis was positioned parallel to the intact limb. Participants were asked to stand upright throughout all tests, without moving their feet or touching the visual surround.

The SOT measured postural sway during three, 20-second trials of six different conditions challenging the visual, vestibular and somatosensory systems during stable and unstable support surface conditions. The order of tests was standardised according to the manufacturer's instructions. An explanation of each of the six conditions is shown in Table 2.

The MCT measured automatic postural reactions following standardised support surface translations. The MCT consisted of graded (small, medium, large) conditions performed backward, then forward. Each condition consisted of three individual translations. The small translation served as a familiarisation so only four conditions were analysed. The distance of the translation was scaled according to the participant's height, causing 1.8° sway for 300ms, and 3.2° sway for 400ms, for the medium and large translations, respectively. Participants kept their eyes open for the duration of the test, and the surround remained fixed throughout the MCT. Latency between the onset of the perturbation and detection of an active force response was calculated by the centre of force generated by each leg independently for 2.5 seconds.

Participants in both groups completed the ABC questionnaire at the same time points as the NeuroCom assessments. The ABC-UK questionnaire[32] comprised 16 questions that asked respondents to indicate their confidence to maintain their balance and remain steady during daily tasks on a scale of zero (no confidence) to 100 (complete confidence); the average of the 16 questions was then used as the overall score. Although not specific to LLA, it has been previously validated in this population and a minimal detectable change of 6 points was determined[33].

Outcome measures

For the SOT, outcome measures included changes in equilibrium and strategy scores, and sensory ratios at baseline and post-intervention. Equilibrium scores were calculated by comparing each participant's maximum anterior-posterior centre of gravity displacement with 12.5°, the theoretical limit of sway stability. If a participant lost their balance, required support from the harness or surround, or used a stepping strategy they were assigned a score of zero for that trial, and this was recorded as a loss of balance (LoB). Equilibrium scores ranged from zero (LoB) to 100 (perfect stability). Therefore it was important to consider LoBs as they influenced equilibrium scores and the subsequently derived sensory ratios. Strategy scores were calculated by comparing each participant's peak-to-peak amplitude of horizontal shear force with the maximum possible shear force of 11.4 kg (25 lbs). Strategy scores ranged from zero (maximal shear force and a full hip strategy) to 100 (little or no shear force and a full ankle strategy). Scores in between were reflective of a combination of hip and ankle strategies. The average equilibrium and strategy scores for the three trials were reported for each condition. An equilibrium composite score was also computed. Sensory ratios were computed for the SOT once equilibrium scores of conditions 1 to 6 were obtained. Calculations and descriptions for each of the four ratios (somatosensory, visual, vestibular and visual preference) are presented in Table 2. Low scores indicated poor use of the respective somatosensory, visual and vestibular systems for postural stability; for the visual preference ratio, a low score indicated a reliance on unstable visual cues rather than more stable somatosensory and vestibular sensory cues.

Outcome measures for the MCT were weight symmetry and intact limb latency at baseline and post-intervention. Previous research has shown that the prosthetic limb does not generate a large enough active force response required to measure latencies[11, 15]; therefore, only the intact limb was investigated. Weight symmetry scores reflected the distribution of total body weight over each limb. The data were scaled to between –100 (total intact limb weight-bearing) to +100 (total prosthetic limb weight-bearing), with zero indicating perfect symmetry[11]. The average latency and weight symmetry scores were computed from the three translations for the four MCT conditions per participant.

For the ABC questionnaire, changes between baseline and post-intervention were investigated. A score of <80% on the self-reported ABC questionnaire indicates the need for further physical therapy interventions for older, able-bodied adults[34]. Typical scores for individuals with an LLA range between 57.5% and 74.8%[33, 35-37].

Statistical analysis

Variables were imported into SPSS, Version 22 for statistical analysis. Data were imputed for three participants (exercise, n=2; control, n=1) where there were missing data with multiple imputation using a Markov chain Monte Carlo fully conditional specification. Statistical differences (P<0.05) between, and within groups, across and at the two different time points (baseline and post-intervention), were assessed using a repeated measures general linear model. Effect size was calculated and reported using Cohen's *d* where <0.41 was deemed negligible, >1.15 as moderate and >2.70 considered as a strong effect size[38].

Results

There were no significant differences between groups for age, height, body mass or time since amputation (Table 1).

Of all the SOT trials completed (14 participants*18 trials/participant), 22 (8.7%) were recorded as a LoB (exercise, n=6; control, n=16) at baseline and 6 (2.4%) were recorded as a LoB (exercise, n=1; control, n=5) at post-intervention. All LoBs occurred during conditions 5 and 6.

In condition 5, the exercise group demonstrated a significantly (*P*=0.023) better equilibrium score compared to the control group at post-intervention (Figure 1a), as well as a significant improvement from baseline with moderate effect size (*P*=0.012, *d*=1.45). No significant changes were observed for the other conditions. Similarly, the exercise group significantly improved their strategy score during condition 5 at post-intervention with a small effect size (*P*=0.028, *d*=0.86; Figure 1b), with higher scores indicating better balance with less reliance on a hip strategy. No other significant changes were observed for the strategy score.

Sensory ratio results are reported in Table 3. Significant changes were seen for the vestibular ratio for the exercise group (*P*=0.009, *d*=1.19) and the control group (*P*=0.037, *d*=0.81), with moderate and small effect sizes, respectively.

In the MCT, during forward displacements, there were significant group*time interactions for medium (*P*=0.029) and large translations (*P*=0.048). Additionally, analysis indicated trends toward greater limb asymmetry for the control group, for both forward-medium (*P*=0.055, *d*=0.42) and forward-large *(P*=0.087, *d*=0.32) translations (Table 3); however, the effect sizes were negligible. No significant interactions or changes were recorded for backward translations. There was a significant increase in latency times during forward-medium translations in the exercise group with a small effect size (*P*=0.036, *d*=0.88; Table 3).

No significant changes were observed for ABC score between any time points or for either group (Table 3).

Discussion

The aim of this study was to evaluate how a 12-week personalised exercise programme affected postural control and self-reported balance confidence for people with an LLA. The results of this study are the first to quantify some improvement in postural control, using CDP, following an exercise programme designed for people with limb loss.

For individuals with an LLA, most falls occur as a result of disruptions to the base of support and intrinsic destabilising factors[17].The equilibrium score of the SOT is determined according to the participant's ability to control their posture for the duration of the trial, without losing their balance. Those who sustained a LoB recorded a score of zero, which influenced their overall score. Therefore, the number of LoBs during the SOT were investigated and reported to understand changes in the equilibrium score and derived sensory ratios. All LoBs occurred during conditions 5 and 6, during which visual input was absent or disrupted, respectively, and somatosensory feedback was inaccurate, concurrently. Therefore the expected sensory system response was from the vestibular system. The exercise group demonstrated a significant improvement in the equilibrium score during condition 5 between the two time points. The improved postural control at post-intervention, compared with baseline, was likely a result of improved interpretation of somatosensory input (even when inaccurate, as this sensory system is most adversely affected by amputation and could be positively affected by exercise), together with the enhanced response from the vestibular system, as evidenced by the significantly higher vestibular ratio, or prior experience of the SOT, or a combination of these. A learning effect has previously been documented for the SOT, and is more substantial in conditions 4 to 6 than 1 to 3[39]. Even so, the SOT has previously been validated for use with individuals who have an LLA, and is sensitive enough to detect even small improvements in postural control[28]. Higher equilibrium scores, suggestive of improved postural control during more challenging balance situations, may mitigate the risk of falling when these scenarios are faced outside of a laboratory setting (e.g., when standing on a moving bus).

The improvement in equilibrium score during condition 5 may also suggest reduced reliance on visual input to maintain postural control. Previous research has shown that lower limb prosthesis users are unlikely to fall during quiet standing even with reduced visual input, and most falls occur during level walking[17], but people with an LLA have a greater reliance on visual input to overcome inaccurate somatosensory feedback[5, 11, 13, 14]. Therefore, in the current study, it was unsurprising that no change in equilibrium score was measured when the eyes were closed and the platform was stable (condition 2), where participants already scored highly at baseline. In the current study, the significant improvement in vestibular ratio overall and in equilibrium score during condition 5 for the exercise group suggests that an exercise intervention wanting to improve balance following LLA could incorporate graded exercises on unstable support surfaces, where the emphasis is on the re-interpretation of somatosensory input, combined with exercises that challenge the vestibular system. Strengthening the other sensory systems could reduce the reliance on visual input for postural control. This is important during more challenging and/or novel balance situations. The exercise group also significantly increased strategy score during condition 5, indicating reduced postural sway during standing with eyes closed and inaccurate somatosensory input, and a greater capacity to maintain balance without having to generate torque about the hip joint (i.e., less reliance on a hip strategy). This finding may be explained by the fact that, unlike the equilibrium score, strategy scores are still calculated when a LoB occurred.

Overall, the exercise intervention did not change the somatosensory or visual sensory ratios as these were already quite high at baseline. Low vestibular ratio scores were seen in both groups at baseline testing, which increased significantly over time with small (d=0.81) and moderate (d=1.18) effect sizes in the control and exercise groups, respectively. Equilibrium scores are used to calculate the sensory ratios; therefore, fewer LoBs occurring post-intervention during condition 5 likely contributed to the significant increase in vestibular ratio scores. Although the exercise intervention did not target any sensory system exclusively, it involved activities that challenged the vestibular system, and this may be a finding worth exploring for future exercise programmes wanting to improve balance.

Both groups demonstrated a stronger intact limb preference for weight-bearing during unstable perturbations. However, after the 12-week intervention period, the control group demonstrated a trend towards more weight-bearing asymmetry, with even greater intact limb reliance after a postural disturbance. This increased asymmetry, demonstrated by the significant group*time interactions during forward perturbations, quantified within a relatively short 12-week period, suggests that a lack of targeted exercise training could be detrimental, perhaps due to increased affected side weakness or disuse. This finding supports the importance of targeted exercise to maintain existing, and ideally increase, lower limb muscle strength as we found that normal daily activities may be insufficient to, thereby prompting increased reliance on the intact limb. In the long-term, weight-bearing asymmetry, as a result of an intact limb preference, as reported in previous studies, has also been associated with the possible development of degenerative musculoskeletal conditions such as osteoarthritis, lower back pain and reduced bone density on the affected limb [40-44].

The latency scores for the participants in the current study (range: 114–154 milliseconds) exceeded the range of 73–110 milliseconds[45] necessary for automatic postural responses, thus indicating reliance on voluntary responses that have a longer latency. The increased time between perturbation onset and centre of force movement for the exercise group was unexpected. However, the exercise intervention emphasised endurance and strength exercises more than power, and did not target latency or time to recover from perturbations (where time is a key factor). Future exercise programmes wanting to focus on latency should include strength and balance exercises with a temporal element, with important safety considerations in a population at high risk of falls.

ABC scores were generally comparable to other studies involving participants with an LLA[33, 35, 36]. Average scores for neither group reached 80%, suggesting that ongoing physical therapy or longer-term exercise training would be beneficial for our cohort of participants[34]. However, the lack of change in ABC scores after 12 weeks was unexpected. Similar findings of ABC scores remaining constant or declining, despite quantifiable improvements in postural control following an exercise intervention, have previously been reported in older, able-bodied adults[46, 47]. Together, these findings suggest that objective changes in standing postural control may not be associated with subjective, self-reported balance confidence during dynamic daily activities. The possible reasons for this outcome include that, as exercises were graded in difficulty throughout the intervention, the absence of mastery did not increase participants' confidence levels, and/or that participants had gained an increased awareness of their falls risk and postural control boundaries as a result of taking part in the intervention[46, 47].

Study limitations

The exercise intervention involved multiple exercise modalities, including balance, strength, endurance and flexibility. We were unable to identify a single or several types of exercise that contributed to the improved postural control that we quantified with CDP. Participants completed at least three, 1-hour sessions weekly (supervised and home-based), increasing over the intervention period, however intensity was not monitored. Therefore we are unable to recommend an optimal exercise dose-response. Although we applied broad inclusion criteria to make the programme as accessible to a heterogeneous group of participants, the large number of participants who were ineligible or declined to take part suggests other important factors need to be considered before implementing an exercise programme successfully in the community. For example, in order to overcome some of the issues around time commitment, transport and cost, delivering supervised exercise sessions virtually could be a viable alternative. A better understanding of the barriers and facilitators to exercise, of participants in the local community, may have resulted in a better uptake to exercise. Broadly speaking, the outcomes of larger, simpler randomised trials can be generalised more easily to the wider population of interest compared to smaller more complex treatments. Participants in this study were a small group completing a multi-component exercise programme that was personalised to their baseline profiles based on rigorous biomechanical assessments. Therefore caution should be applied when interpreting the results as this limits our ability to generalise the findings to other individuals with an LLA undertaking exercise.

Conclusions

This study is the first to quantify the effects of a personalised exercise programme on postural control for people with an LLA. Improvements in postural control, as evidenced by the SOT higher equilibrium and strategy scores and vestibular ratio, particularly in challenging, unstable conditions with the eyes closed, may indicate reduced reliance on visual input, with enhanced somatosensory awareness and vestibular function, following an exercise intervention. A group*time interaction indicating increased MCT weight asymmetry in the control group suggested that normal daily activities (i.e., no exercise, even over a 12-week period) lead to greater reliance on the intact limb after a perturbation, which could have long-term, negative effects. Future studies may identify an optimal exercise modality and dose-response, and enhance balance training to reduce postural response latency.

Figure captions

Figure 1. (A) Equilibrium and composite; and (B) strategy scores for SOT conditions one to six with Exercise group n=7 and Control group n=7

Footnotes: (A) Scores closer to 100 indicate perfect stability, and scores closer to zero indicate instability. A score of zero indicates a loss of balance; (B) Scores closer to 100 indicate an ankle strategy, with scores closer to zero indicating more reliance on a hip strategy. Scores in between represent a combination of ankle and hip strategies.

* indicates a significant (P<0.05) difference between PRE and POST.

COMP: composite score; PRE: baseline measure; POST: follow-up measure; SOT: Sensory Organization Test.

References

[1] F.B. Horak, S.M. Henry, A. Shumway-Cook, Postural perturbations: New insights for treatment of balance disorders, Phys. Ther. 77(5) (1997) 517-533. <Go to ISI>://WOS:A1997WY50200007.

[2] A.S. Pollock, B.R. Durward, P.J. Rowe, J.P. Paul, What is balance?, Clinical Rehabilitation 14(4) (2000) 402-406. <Go to ISI>://WOS:000088484400006.

[3] T.M. Quai, S.G. Brauer, J.C. Nitz, Somatosensation, circulation and stance balance in elderly dysvascular transtibial amputees, Clinical Rehabilitation 19(6) (2005) 668-676. <Go to ISI>://WOS:000231527500012.

[4] P. Hlavackova, C. Franco, B. Diot, N. Vuillerme, Contribution of each leg to the control of unperturbed bipedal stance in lower limb amputees: new insights using entropy, PLoS One 6(5) (2011) e19661-e19661. https://pubmed.ncbi.nlm.nih.gov/21603630

[5] C.T. Barnett, N. Vanicek, R.C.J. Polman, Postural responses during volitional and perturbed dynamic balance tasks in new lower limb amputees: A longitudinal study, Gait Posture 37(3) (2013) 319-325. <Go to ISI>://WOS:000316647500003.

[6] A.H. Vrieling, H.G. van Keeken, T. Schoppen, E. Otten, A.L. Hof, J.P.K. Halbertsma, et al., Balance control on a moving platform in unilateral lower limb amputees, Gait Posture 28(2) (2008) 222-228. <Go to ISI>://WOS:000258249500007.

[7] C.R. Claret, G.W. Herget, L. Kouba, D. Wiest, J. Adler, V. von Tscharner, et al., Neuromuscular adaptations and sensorimotor integration following a unilateral transfemoral amputation, J. NeuroEng. Rehabil. 16(1) (2019) 115-115. https://pubmed.ncbi.nlm.nih.gov/31521190

[8] J.S. Petrofsky, I.A. Khowailed, Postural Sway and Motor Control in Trans-Tibial Amputees as Assessed by Electroencephalography during Eight Balance Training Tasks, Med. Sci. Monitor 20 (2014) 2695-2704. <Go to ISI>://WOS:000350159500001.

[9] N.P. Fey, A.K. Silverman, R.R. Neptune, The influence of increasing steady-state walking speed on muscle activity in below-knee amputees, J. Electromyogr. Kinesiol. 20(1) (2010) 155-161. <Go to ISI>://WOS:000273621100021.

[10] J.O. Judge, M.B. King, R. Whipple, J. Clive, L.I. Wolfson, Dynamic balance in older persons - effects of reduced visual and proprioceptive input, Journals of Gerontology Series a-Biological Sciences and Medical Sciences 50(5) (1995) M263-M270. <Go to WoS>://WOS:A1981MK87900002.

[11] N. Vanicek, S. Strike, L. McNaughton, R. Polman, Postural Responses to Dynamic Perturbations in Amputee Fallers Versus Nonfallers: A Comparative Study With Able-Bodied Subjects, Arch. Phys. Med. Rehabil. 90(6) (2009) 1018-1025. <Go to ISI>://WOS:000266787000017.

[12] D. Bolger, L.H. Ting, A. Sawers, Individuals with transtibial limb loss use interlimb force asymmetries to maintain multi-directional reactive balance control, Clin. Biomech. 29(9) (2014) 1039-1047. <Go to ISI>://WOS:000346222100014.

[13] G.R. Fernie, P. Eng, P.J. Holliday, Postural sway in amputees and normal subjects, J. Bone Joint Surg.-Am. Vol. 60(7) (1978) 895-898. <Go to ISI>://WOS:A1978FV98700003.

[14] E. Isakov, J. Mizrahi, Z. Susak, I. Ona, N. Hakim, Influence of prosthesis alignment on the standing balance of below-knee amputees, Clin. Biomech. 9(4) (1994) 258-262. <Go to WoS>://WOS:A1989U198800001.

[15] F. Molina-Rueda, A. Molero-Sanchez, I.M. Alguacil-Diego, M. Carratala-Tejada, A. Cuesta-Gomez, J.C. Miangolarra-Page, Weight Symmetry and Latency Scores for Unexpected Surface Perturbations in Subjects With Traumatic and Vascular Unilateral Transtibial Amputation, Pm&R 8(3) (2016) 235-240. <Go to ISI>://WOS:000372434900006.

[16] W.C. Miller, M. Speechley, B. Deathe, The prevalence and risk factors of falling and fear of falling among lower extremity amputees, Arch. Phys. Med. Rehabil. 82(8) (2001) 1031-1037. <Go to ISI>://WOS:000170275000004.

[17] J. Kim, M.J. Major, B. Hafner, A. Sawers, Frequency and Circumstances of Falls Reported by Ambulatory Unilateral Lower Limb Prosthesis Users: A Secondary Analysis, PM & R : the journal of injury, function, and rehabilitation 11(4) (2019) 344-353.

[18] N.D. Vieira, D. Testa, P.C. Ruas, T.D. Salvini, A.M. Catai, R.C. Melo, The effects of 12 weeks Pilates-inspired exercise training on functional performance in older women: A randomized clinical trial, J.Bodyw. Mov. Ther. 21(2) (2017) 251-258. <Go to ISI>://WOS:000403104100005.

[19] T. Lelard, P.L. Doutrellot, P. David, S. Ahmaidi, Effects of a 12-Week Tai Chi Chuan Program Versus a Balance Training Program on Postural Control and Walking Ability in Older People, Arch. Phys. Med. Rehabil. 91(1) (2010) 9-14. <Go to ISI>://WOS:000277417300002.

[20] A. Pluchino, S.Y. Lee, S. Asfour, B.A. Roos, J.F. Signorile, Pilot Study Comparing Changes in Postural Control After Training Using a Video Game Balance Board Program and 2 Standard Activity-Based Balance Intervention Programs, Arch. Phys. Med. Rehabil. 93(7) (2012) 1138-1146. <Go to ISI>://WOS:000306208800004.

[21] E.F. Youssef, A.A. Shanb, Supervised Versus Home Exercise Training Programs on Functional Balance in Older Subjects, Malays. J. Med. Sci. 23(6) (2016) 83-93. <Go to ISI>://WOS:000398457100009.

[22] C. Fukusaki, K. Masani, M. Miyasaka, K. Nakazawa, Acute positive effects of exercise on center-of-pressure fluctuations during quiet standing in middle-aged and elderly women, J. Strength Cond. Res. 30(1) (2016) 208-216. <Go to WoS>://WOS:A1994NT78500007.

[23] K.R. Kaufman, M.P. Wyatt, P.H. Sessoms, M.D. Grabiner, Task-specific Fall Prevention Training Is Effective for Warfighters With Transtibial Amputations, Clin. Orthop. Rel. Res. 472(10) (2014) 3076-3084. <Go to ISI>://WOS:000341909300024.

[24] Z. Matjacic, H. Burger, Dynamic balance training during standing in people with trans-tibial amputation: a pilot study, Prosthet. Orthot. Int. 27(3) (2003) 214-220. <Go to ISI>://WOS:000187737700007.

[25] C.A. Miller, J.E. Williams, K.L. Durham, S.C. Hom, J.L. Smith, The effect of a supervised community-based exercise program on balance, balance confidence, and gait in individuals with lower limb amputation, Prosthet. Orthot. Int. 41(5) (2017) 446-454. <Go to ISI>://WOS:000411826600002.

[26] Z.A. Schafer, J.L. Perry, N. Vanicek, A personalised exercise programme for individuals with lower limb amputation reduces falls and improves gait biomechanics: A block randomised controlled trial, Gait Posture 63 (2018) 282-289.

[27] C.C. Harro, C. Garascia, Reliability and Validity of Computerized Force Platform Measures of Balance Function in Healthy Older Adults, Journal of geriatric physical therapy (2001) 42(3) (2019) E57-e66.

[28] P. Jayakaran, G.M. Johnson, S.J. Sullivan, Test-Retest Reliability of the Sensory Organization Test in Older Persons With a Transtibial Amputation, Pm&R 3(8) (2011) 723-729. <Go to ISI>://WOS:000305438000007.

[29] C.T. Barnett, N. Vanicek, D.F. Rusaw, Do Predictive Relationships Exist Between Postural Control and Falls Efficacy in Unilateral Transtibial Prosthesis Users?, Arch Phys Med Rehabil 99(11) (2018) 2271-2278.

[30] K.R. Kaufman, J.A. Levine, R.H. Brey, B.K. Iverson, S.K. McCrady, D.J. Padgett, et al., Gait and balance of transfemoral amputees using passive mechanical and microprocessor-controlled prosthetic knees, Gait Posture 26(4) (2007) 489-493. http://www.sciencedirect.com/science/article/pii/S0966636207001853.

[31] L.M. Nashner, G. McCollum, The organization of human postural movements - a formal basis and experimental synthesis, Behav. Brain Sci. 8(1) (1985) 135-150. <Go to ISI>://WOS:A1985ANN3200080.

[32] S.W. Parry, N. Steen, S.R. Galloway, R.A. Kenny, J. Bond, Falls and confidence related quality of life outcome measures in an older British cohort, Postgrad. Med. J. 77(904) (2001) 103-108. <Go to ISI>://WOS:000166726700009.

[33] W.C. Miller, A.B. Deathe, M. Speechley, Psychometric properties of the activities-specific balance confidence scale among individuals with a lower-limb amputation, Arch. Phys. Med. Rehabil. 84(5) (2003) 656-661. <Go to ISI>://WOS:000182700900006.

[34] A.M. Myers, P.C. Fletcher, A.H. Myers, W. Sherk, Discriminative and evaluative properties of the activities-specific balance confidence (ABC) scale, Journals of Gerontology Series a-Biological Sciences and Medical Sciences 53(4) (1998) M287-M294. <Go to ISI>://WOS:000074880100018.

[35] W.C. Miller, A.B. Deathe, M. Speechley, J. Koval, The influence of falling, fear of falling, and balance confidence on prosthetic mobility and social activity among individuals with a lower extremity amputation, Arch. Phys. Med. Rehabil. 82(9) (2001) 1238-1244. <Go to ISI>://WOS:000170873900015.

[36] C.K. Wong, C.C. Chen, S.A. Benoy, R.T. Rahal, W.M. Blackwell, Role of balance ability and confidence in prosthetic use for mobility of people with lower-limb loss, J. Rehabil. Res. Dev. 51(9) (2014) 1353-1364. <Go to ISI>://WOS:000350836500003.

[37] C.K. Wong, J.E. Ehrlich, J.C. Ersing, N.J. Maroldi, C.E. Stevenson, M.J. Varca, Exercise programs to improve gait performance in people with lower limb amputation: A systematic review, Prosthet. Orthot. Int. 40(1) (2016) 8-17. <Go to ISI>://WOS:000368544000001.

[38] C.J. Ferguson, An Effect Size Primer: A Guide for Clinicians and Researchers, Prof. Psychol.-Res. Pract. 40(5) (2009) 532-538. <Go to ISI>://WOS:000270927100014.

[39] D.M. Wrisley, M.J. Stephens, S. Mosley, A. Wojnowski, J. Duffy, R. Burkard, Learning effects of repetitive administrations of the sensory organization test in healthy young adults, Arch Phys Med Rehabil 88(8) (2007) 1049-54.

[40] A.J. Yoder, A.J. Petrella, A.K. Silverman, Trunk-pelvis motion, joint loads, and muscle forces during walking with a transtibial amputation, Gait Posture 41(3) (2015) 757-762. <Go to ISI>://WOS:000353209200003.

[41] M.J. Burke, V. Roman, V. Wright, Bone and joint changes in lower-limb amputees, Ann. Rheum. Dis. 37(3) (1978) 252-254. <Go to WoS>://WOS:000367792600024.

[42] E. Probsting, S. Blumentritt, A. Kannenberg, Changes in the Locomotor System as a Consequence of Amputation of a Lower Limb, Zeitschrift fur Orthopadie und Unfallchirurgie 155(1) (2017) 77-91.

[43] A.L. Pruziner, K.M. Werner, T.J. Copple, B.D. Hendershot, E.J. Wolf, Does intact limb loading differ in servicemembers with traumatic lower limb loss?, Clin Orthop Relat Res 472(10) (2014) 3068-75.

[44] K.R. Kaufman, S. Frittoli, C.A. Frigo, Gait asymmetry of transfemoral amputees using mechanical and microprocessor-controlled prosthetic knees, Clin Biomech (Bristol, Avon) 27(5) (2012) 460-465. https://pubmed.ncbi.nlm.nih.gov/22221344

[45] F.B. Horak, L.M. Nashner, Central programming of postural movements - adaptation to altered support-surface configurations, Journal of Neurophysiology 55(6) (1986) 1369-1381. <Go to WoS>://WOS:A1993LE93500015.

[46] L.K. Allison, T. Kiemel, J.J. Jeka, Sensory-Challenge Balance Exercises Improve Multisensory Reweighting in Fall-Prone Older Adults, Journal of Neurologic Physical Therapy 42(2) (2018). https://journals.lww.com/jnpt/Fulltext/2018/04000/Sensory_Challenge_Balance_Exercises_Improve.6.aspx.

[47] K.P. Westlake, E.G. Culham, Sensory-Specific Balance Training in Older Adults: Effect on Proprioceptive Reintegration and Cognitive Demands, Phys. Ther. 87(10) (2007) 1274-1283. https://doi.org/10.2522/ptj.20060263.

Suppliers

a. Version 8.1.0; NeuroCom International Inc., 9570 SE Lawnfield Road, Clackamas, Oregon, 97015

Table 1. Participant baseline demographics including prosthetic componentry.

	Exercise group (n=7)	Control group (n=7)
Sex, male/female, n	4/3	7/0
Age, years, mean (SD)	60 (12)	63 (17)
Height, cm, mean (SD)	172 (10)	178 (7)
Body mass, kg, mean (SD)	92 (15)	101 (21)
Time since amputation, years, mean (SD)	10 (17)	18 (21)
Level of amputation, n (%)		
Transfemoral	5 (71)	5 (71)
Transtibial	2 (29)	2 (29)
Reason for amputation, n (%)		
Vascular	3 (43)	2 (29)
Trauma	1 (14)	3 (43)
Other	3 (43)	2 (29)
Prosthetic knee*, n (%)		
Monocentric	1 (20)	2 (40)
Polycentric	3 (60)	3 (60)
Microprocessor	1 (20)	-
Prosthetic ankle		
SACH	4 (57)	4 (57)
Other	3 (43)	3 (43)

b. *n=5, transfemoral amputees only.
SACH, solid ankle cushion heel

Table 2. Conditions of the Sensory Organization Test and sensory ratios

Condition	Eyes Open/Closed	Description	Feedback removed/inaccurate
1	Open	Fixed visual surround and support surface	None
2	Closed	Fixed visual surround and support surface	Visual feedback removed
3	Open	Sway-referenced visual surround; fixed support surface	Visual feedback inaccurate
4	Open	Fixed visual surround; sway-referenced support surface.	Somatosensory feedback inaccurate
5	Closed	Fixed visual surround; sway-referenced support surface.	Somatosensory feedback inaccurate and visual feedback removed
6	Open	Sway-referenced visual surround and support surface	Somatosensory and visual feedback inaccurate

Ratio Name	Ratio Pair	Description
Somatosensory	$\frac{\text{Condition 2}}{\text{Condition 1}}$	Ability to utilise somatosensory input to maintain balance
Visual	$\frac{\text{Condition 4}}{\text{Condition 1}}$	Ability to utilise visual input to maintain balance
Vestibular	$\frac{\text{Condition 5}}{\text{Condition 1}}$	Ability to utilise vestibular input to maintain balance
Visual Preference	$\frac{\text{Condition 3 + 6}}{\text{Condition 2 + 5}}$	Degree to which there is reliance on visual input to maintain balance, even when the information is inaccurate

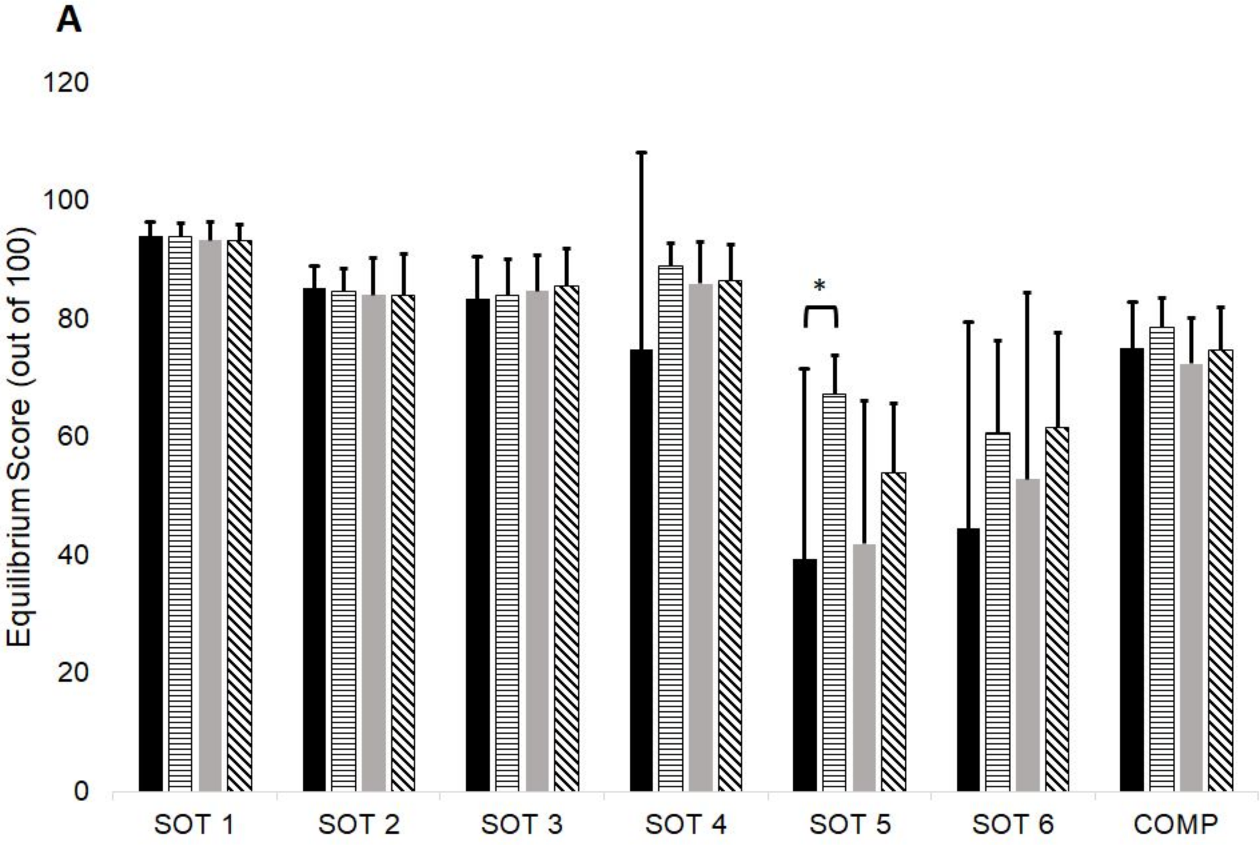
Table 3. Sensory ratio during the SOT; latency times (milliseconds) and weight symmetry scores (–100 to 100) during the MCT; and total ABC scores.

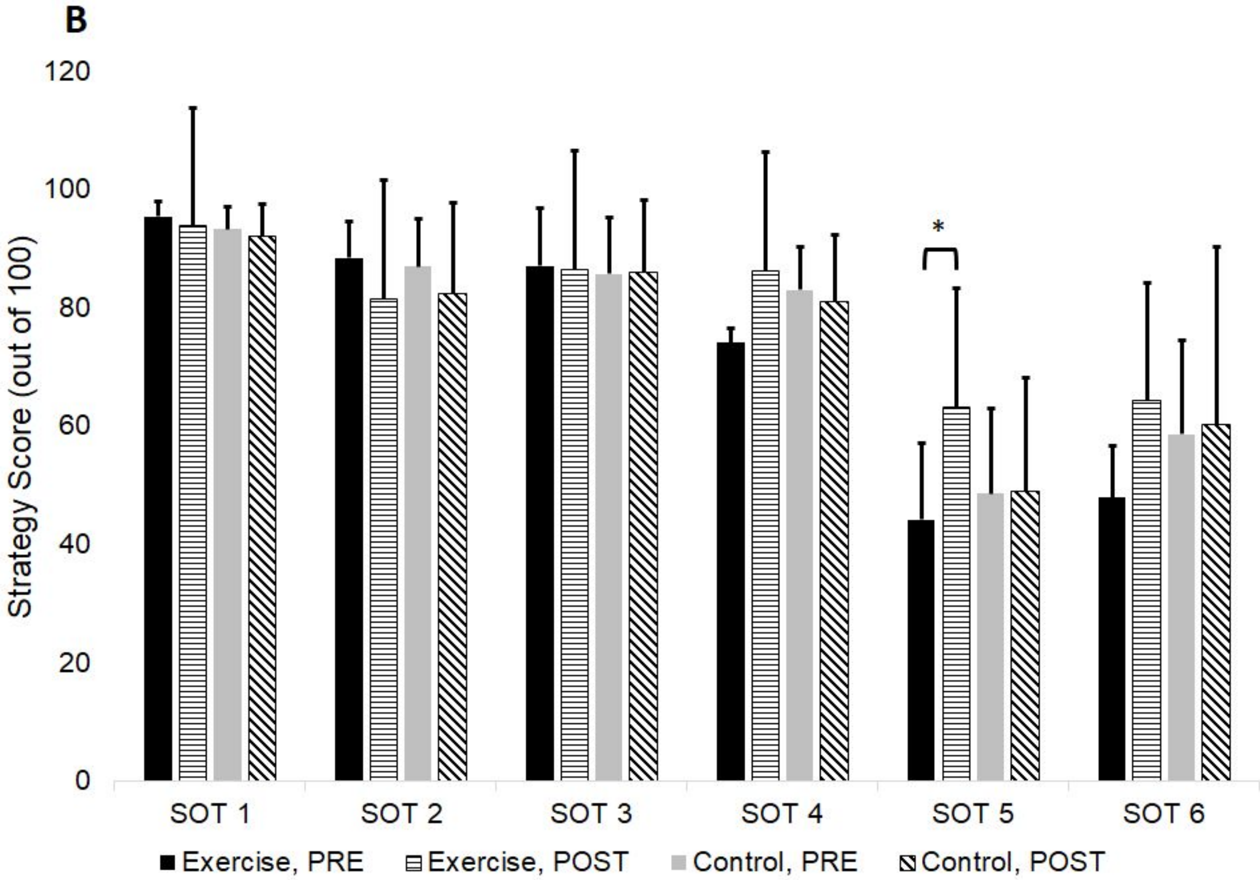
		Exercise group (n=7)					C	
		PRE	POST	95% CI	*P*	*d*	PRE	POS
SOT sensory ratios	Somatosensory	90.6 (3.1)	87.9 (4.1)	–0.5, 6.1	0.092	0.75	91.2 (5.2)	91.0 (
	Visual	92.1 (4.2)	93.6 (5.5)	–4.8, 1.8	0.336	0.31	92.2 (5.4)	93.8 (
	Vestibular	44.4 (30.5)	69.2 (11.2)	–42.1, –7.5	0.009*	1.19	33.3 (26.5)	50.7 (
	Visual preference	105.5 (10.4)	92.9 (11.8)	–4.0, 29.0	0.125	1.14	109.5 (26.2)	112.0 (
MCT latency scores	Backwards							
	Medium	152.9 (48.9)	144.3 (11.3)	–22.0, 39.2	0.553	0.29	144.3 (19.0)	145.7 (
	Large	151.4 (19.5)	135.7 (12.7)	–25.0, 56.4	0.417	0.98	125.7 (56.8)	142.9 (
	Forwards							
	Medium	120.0 (54.2)	150.0 (14.1)	–57.6, –2.4	0.036*	0.88	152.9 (18.0)	154.3 (
	Large	115.7 (52.6)	114.3 (53.5)	–45.3, 48.2	0.948	0.03	138.6 (14.6)	145.7 (
MCT weight symmetry scores	Backwards							
	Medium	–27.0 (18.2)	–21.0 (12.6)	–13.7, 1.7	0.117	0.39	–31.6 (25.3)	–33.6 (
	Large	–25.3 (19.2)	–22.2 (7.9)	–15.5, 9.4	0.599	0.23	–27.1 (26.0)	–32.4 (
	Forwards							
	Medium†	–24.6 (18.6)	–18.0 (8.4)	–17.0, 3.8	0.191	0.49	–22.6 (21.4)	–32.7 (
	Large†	–24.6 (20.9)	–19.1 (10.6)	–15.1, 4.0	0.233	0.35	–25.6 (22.8)	–33.8 (
ABC score	Total score	62.1 (26.2)	67.2 (15.3)	–21.8, 11.6	0.518	0.25	74.2 (19.9)	76.4 (

PRE & POST values are mean (SD).

Higher scores indicate greater postural control for the somatosensory, visual and vestibular ratios, scores nearer 100 indicate greater postural control for the visual preference ratio.

A score of –100 for weight symmetry indicates total intact limb weight-bearing, +100 indicates total prosthetic limb weight-bearing, and zero indicates perfect symmetry.
* indicates a significant (*P*<0.05) change; † indicates a significant (*P*<0.05) group*time interaction.
ABC, Activities-specific Balance Confidence questionnaire; MCT, Motor Control Test; PRE, baseline measure; POST, post-intervention measure; SOT, Sensory Organization Test.


A
Equilibrium Score (out of 100)
120
100
80
60
40
20
0
*
SOT 1
SOT 2
SOT 3
SOT 4
SOT 5
SOT 6
COMP


B
Strategy Score (out of 100)
120
100
80
60
40
20
0
*
SOT 1
SOT 2
SOT 3
SOT 4
SOT 5
SOT 6
Exercise, PRE
Exercise, POST
Control, PRE
Control, POST