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Gait & Posture xxx (2012) xxx–xxx

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1 Highlights

Gait & Posture xxx (2012) xxx

Postural responses during volitional and perturbed dynamic balance tasks in new lower limb amputees: A longitudinal study

C.T. Barnett *, N. Vanicek, R.C.J. Polman

▶ Postural responses during balance tasks in new transtibial amputees following discharge from rehabilitation were examined. ▶ Amputees increased utilisation of the ankle strategy and somatosensory input. ▶ Despite improvements, amputees were heavily reliant upon vision to maintain balance. ▶ Amputees increased the spatial and accuracy aspects but not temporal aspects of postural control, suggesting a trade-off. ▶ These results have important implications for amputee postural control and rehabilitation.

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Gait & Posture xxx (2012) xxx–xxx

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Postural responses during volitional and perturbed dynamic balance tasks in new lower limb amputees: A longitudinal study

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ARTICLE INFO

Article history:
Received 28 August 2011
Received in revised form 29 April 2012
Accepted 26 July 2012

Keywords:
Balance
Postural control
Transtibial
Amputee
Rehabilitation

ABSTRACT

This study examined the adaptation of postural responses in transtibial amputees during both perturbed and volitional dynamic balance tasks during a five-month period following discharge from inpatient rehabilitation. Seven unilateral transtibial amputees performed the sensory organisation test (SOT) and the limits of stability (LOS) test protocols on the NeuroCom Equitest® at one, three and six months post-discharge from in-patient rehabilitation. Overall balance ability improved significantly ($p = 0.01$) following discharge as did utilisation of somatosensory input ($p = 0.01$), with hip strategy use decreasing. Reaction time and movement velocity did not change significantly in the majority of target directions for the LOS test. However, endpoint COG excursion and directional control were significantly increased in a number of directions ($p \leq 0.05$). Although balance ability improved following discharge from rehabilitation, participants were heavily reliant upon vision in order to maintain balance. Following discharge from rehabilitation, amputees were seemingly able to increase the spatial and accuracy aspects of volitional exploration of their LOS. However, temporal aspects did not display any adaptation, suggesting a trade-off between these aspects of postural control. Further practice of performing volitional postural movements under increasing time pressure, for example using low-cost gaming tools, may improve balance ability and postural control.

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1. Introduction

The control of posture to maintain balance requires the ability to correctly predict, detect and encode perturbations [1]. To successfully maintain balance by keeping the centre of gravity (COG) within the base of support (BOS), a number of strategies are employed during both static and dynamic conditions. Movements at the ankle joint (ankle strategy) are utilised in response to smaller, low frequency perturbations; movements at the hip (hip strategy) are utilised in response to larger, high frequency perturbations; whilst a stepping strategy is utilised to rapidly change the dimensions of the BOS in relation to the COG [1,2].

Lower limb amputation results in a loss of afferent nerve pathways and a potential distortion in somatosensory information provided to the central nervous system [3–5]. In addition, the loss of the biological ankle joint and associated musculature may result in reduced joint mobility and muscle strength. Consequently, these factors may adversely affect amputees' ability to maintain balance successfully which is of particular relevance to recent amputees who are still adjusting to their altered lower limb mechanics and new biomechanical constraints.

Lower limb amputees have been shown to have poorer balance compared to able-bodied individuals [6–9] and use the intact limb as a primary means of control during static and dynamic tasks, while relying heavily on visual information [7–10]. Consequently, amputees are at a higher risk of falling when compared to age-matched able-bodied individuals [11]. Computerised dynamic posturography (CDP) is a sophisticated way to assess lower limb amputee balance ability [10]. One advantage of CDP is the ability to assess postural sway whilst manipulating an individual's sensory environment to assess the contributions of visual, vestibular and somatosensory information objectively whilst maintaining balance.

Studies investigating the longitudinal adaptations in balance ability and postural control incorporating repeated measure study designs in lower limb amputees are limited, although one study reported a reduction (improvement) in static postural sway during rehabilitation [6]. Much research has focused upon external perturbations to amputees balance system with no reports on lower limb amputees' volitional ability to control posture to

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http://dx.doi.org/10.1016/j.gaitpost.2012.07.023

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explore their limits of stability (LOS) [8–10]. In addition, studies have reported results from amputees that may not be typically representative of the wider amputee population [8,9]. Understanding how amputees learn to respond to external perturbations and when volitionally controlling postural movements could have important implications for lower limb amputee patients and associated therapists with reference to rehabilitation and falls prevention. Therefore, the current study assessed the adaptation of postural responses in transtibial amputees during both perturbed and volitional dynamic balance tasks during a five-month period following discharge from inpatient rehabilitation.

2. Methods

2.1. Participants

Seven unilateral transtibial amputees (Table 1) gave informed consent to participate in the current study. Participants were excluded if they had any current musculoskeletal injuries, cognitive deficits or experienced pain or discomfort whilst using their prostheses. Participants were included if they were at least 18 years of age, had completed the course of in-patient rehabilitation and were able to walk unaided for five metres. The study was approved by the NHS Local Research Ethics Committee (Ref.: 08/H1304/10). Participants attended a standardised number of data collection sessions at one, three and six months following discharge from rehabilitation. These time points were selected in order to assess longitudinal adaptations in balance and postural control.

2.2. Experimental setup and protocol

Participants' height (cm) and mass (kg) were recorded using a free-standing height measure and column beam scale (Seca, Birmingham, UK) and entered into the NeuroCom Equitest® software (Neurocom International Inc., Clackamas, US) along with age. Participants wore their own comfortable, flat footwear during all data collection sessions and were fitted into an overhead safety harness to prevent falls whilst allowing movement beyond their theoretical limits of stability. The NeuroCom Equitest® was used to assess postural responses during the sensory organisation test (SOT) (Fig. 1A) and limits of stability test (LOS) (Fig. 1B) protocols. The malleoli of the intact limb and prosthetic ankle joint on the affected limb were aligned with the axis of rotation of the support platform. Two force plates, connected by a central pin joint and capable of anterior–posterior (A–P) translation and sagittal plane rotation, sampled vertical and shear forces at 100 Hz via four force transducers mounted on a central plate and a fifth transducer bracketed to the central plate, respectively. The visual surround rotated in the sagittal plane with a maximum velocity of 15° s^{-1} and was referenced to the centre of force position (sway-referenced). Force magnitude and centre data were used to calculate SOT and LOS performance scores in NeuroCom Equitest® software, where larger excursions typified reduced postural control (NeuroCom International Inc., Clackamas, US).

2.3. The sensory organisation test

The SOT protocol assessed participants' balance ability by investigating the postural responses to external perturbations. During the SOT protocol, participants were instructed to stand upright and if they reached out to touch the surround or stepped out of position the trial was marked as a 'fall'. Although, no participants in the current study had a score marked as a 'fall' the NeuroCom Equitest® software requires that these trials are scored zero and included as part of the analysis [12]. The standardised order of the SOT consisted of measuring postural sway during six different test conditions, outlined in Fig. 1A [10,13]. Definitions of equilibrium, strategy and sensory analysis scores calculated from the SOT protocol are outlined in Table 2 and have been detailed previously [10,13].

2.4. The limits of stability test

The LOS test protocol assessed participants' ability to volitionally perturb balance in order to explore their LOS. Participants were informed not to move their feet during the LOS unless necessary to avoid falling. Participants were required to voluntarily displace their COG, via a visual representation of their COG on a screen, towards eight pre-determined target positions, as quickly and as accurately as possible (Fig. 1B). Modelling the body as an inverted pendulum, target positions based upon participant height were representative of the 100% limit of stability possible before COG position necessitated adjustment of the base of support [14].

Participants were given a short period of familiarisation where they became accustomed to the COG display. Eight-second trials commenced with participants holding the COG at the start position and, at the onset of a visual cue, displacing the COG towards and hovering over, or as close as possible to, the intended target position until the trial concluded. The sequence of targets was completed in a standardised clockwise direction, starting with position one, using a single trial for each target direction. Reaction time (s), movement velocity (° s^{-1}), endpoint COG excursion (%) and directional control (%) were calculated for each direction of the LOS test protocol (Table 2).

2.5. Statistical analysis

Dependent variables were analysed using a linear mixed model, with repeated measures on the factor time (one month, three months and six months). Time and condition (SOT condition) were modelled as a fixed effects with the appropriate model being

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Table 1
Individual characteristics and prosthetic components of unilateral transtibial amputees.

Gender (M/F)	Age (years)	Height (m)	Mass (kg)	Amputated limb (R/L)	Cause of amputation	Functional prosthetic components	
M	44	1.77	76.5	R	Non-vascular	Renegade freedom foot*	All ankle feet complexes allowed for similar axial movement with the addition of specific differences highlighted
M	63	1.74	83.7	L	Non-vascular	Tres foot with torque absorber	
M	44	1.82	81.0	R	Non-vascular	Renegade freedom foot*	
M	75	1.93	101.9	L	Vascular	Multiflex ankle and foot	
M	50	1.83	106.6	R	Vascular	Senator freedom foot‡	
M	41	1.92	95.4	R	Vascular	Multiflex ankle and foot	
M	70	1.74	96.7	R	Vascular	Multiflex ankle and foot	
(Mean ± SD)	56.1 ± 14.9	1.82 ± 0.08	91.7 ± 11.4				

* Shock absorbing ankle foot complex.
‡ Energy returning ankle foot complex for low to moderately active amputees.

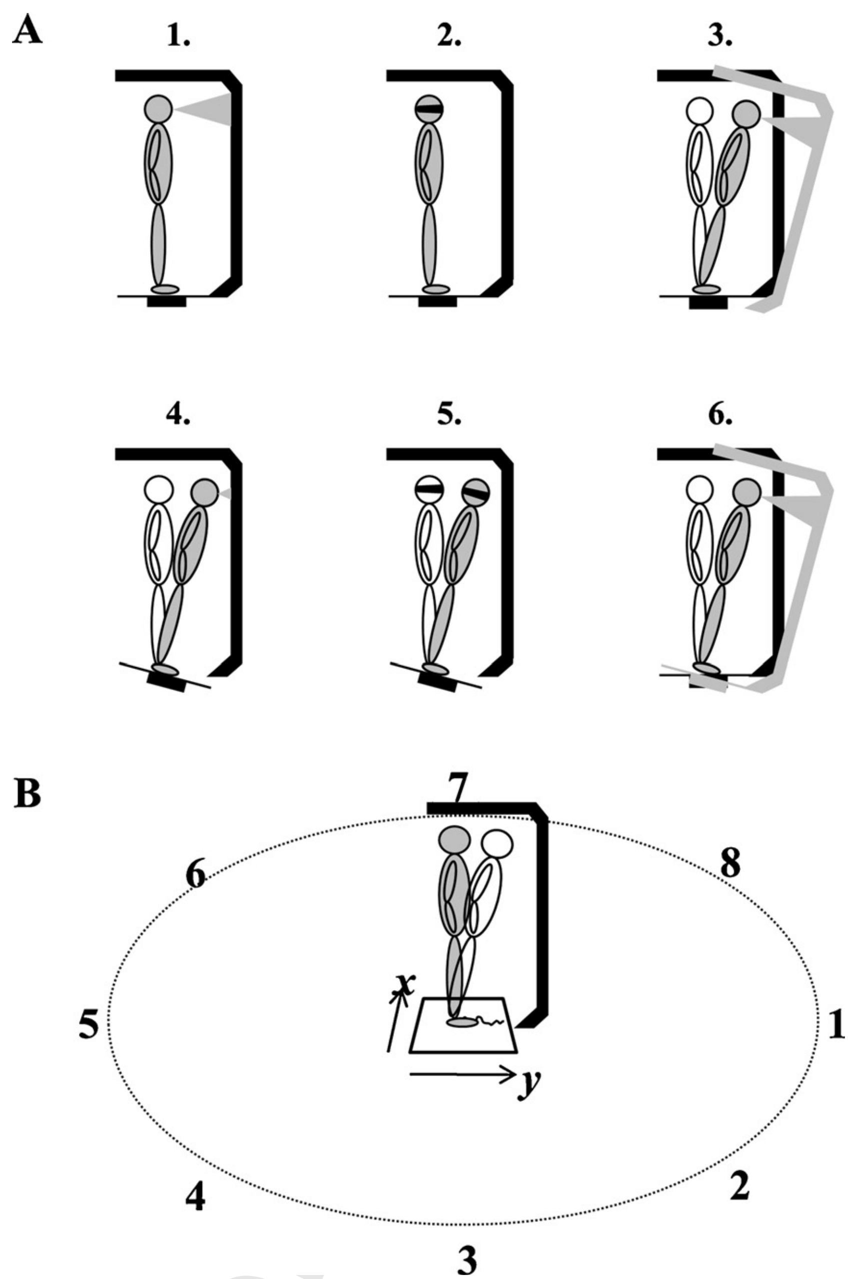

Fig. 1. (A) Representation of the six test conditions of the sensory organisation test (SOT). Condition one – normal vision, static support; condition two – eyes closed, static support (no visual cues); condition three – vision sway-referenced (visual cues are inaccurate), static support; condition four – normal vision, sway-referenced support (somatosensory cues are inaccurate); condition five – eyes closed, sway-referenced support (no visual cues and inaccurate somatosensory cues) and condition six – vision and support both sway-referenced (visual and somatosensory cues are inaccurate) and (B) a schematic representation of the test protocol of the limits of stability (LOS) test. LOS directions defined as: 1 – forward, 2 – affected forward, 3 – affected, 4 – affected back, 5 – back, 6 – intact back, 7 – intact and 8 – intact forward. LOS data for left sided amputees (n = 2) were normalised by switching data from corresponding directions containing a M–L term e.g. left forward became right forward and subsequently 3 – affected forward. (Image used courtesy of NeuroCom International Inc.)

selected according to the lowest value for Hurvich and Tsai's Criterion (AICC). Post hoc comparisons of significant effects were conducted using a Sidak adjustment in SPSS v.17.0 (SPSS Inc., Chicago, USA). The alpha level of statistical significance was set at $p \leq 0.05$.

3. Results

3.1. Sensory organisation test

Composite equilibrium scores indicated that participants' overall balance ability improved significantly (15.2%) between one and six months (p = 0.01) post-discharge and no trials were marked as a fall (Table 3). With the exception of condition four, where a significant decrease between one and three months (p = 0.05) was observed, improvements were significant between one and six months during conditions two (9.8%) (p = 0.02), three (20.3%) (p = 0.05) and six (32.6%) (p = 0.01). No significant effects were observed for equilibrium scores from conditions one or five. This highlighted that the largest improvement in balance ability occurred during the most challenging task conditions. Equilibrium scores were significantly lower with increasing task difficulty (Table 3) ($p < 0.01$).

Table 3 illustrates that during more dynamic and challenging task conditions with greater sensory perturbation, participants' strategy scores were lower ($p < 0.01$). However, observable

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Table 2
Ratio pairings of equilibrium scores used to indicate level of sensory input use during the SOT protocol.

SOT dependant variables	Description	Calculation	Scoring
Equilibrium scores	Sway amplitude whilst maintaining balance during the SOT conditions	Mean observed A–P COG excursion contrasted against a maximal theoretical limit of 12.5° sway	Increased sway amplitude and shear force production, resulted in a lower equilibrium scores on a scale of 0 (poor balance) to 100 (perfect balance)
Composite equilibrium score	Overall sway amplitude whilst maintaining balance during the SOT protocol	Mean of conditions one and two mean scores and each trial score from conditions three, four, five and six	Lower composite equilibrium scores rated on a scale of 0 (poor balance) to 100 (perfect balance)
Strategy scores	Participants use of movements about the ankle and/or hip whilst maintaining balance	Contrast of timing and amplitude of the peak to peak shear force produced against the maximal possible shear force	Higher scores inferred ankle strategy use with lower scores inferring hip strategy use
Sensory analysis			
Somatosensory	Participant's use of somatosensory input	$\frac{\text{Condition two mean}}{\text{Condition one mean}}$	Higher score related to increased use of sensory input
Visual	Participant's use of visual input.	$\frac{\text{Condition four mean}}{\text{Condition one mean}}$	
Vestibular	Participant's use of vestibular input	$\frac{\text{Condition five mean}}{\text{Condition one mean}}$	
Preference	Participant's reliance on visual information when visual information is incorrect.	$\frac{\text{Conditions three + six means}}{\text{Conditions two + five means}}$	Higher score related to increased reliance on visual input, when visual input was inaccurate

LOS dependant variables	Description	Calculation	Scoring
Reaction time	Reaction time when initiating postural movements	Time between the onset of the visual cue, to the initiation of COG excursion	Increased reaction time (s) related to reduced performance
Movement velocity	Angular velocity of postural movements when displacing COG	Angular velocity of postural movements when displacing COG towards target directions	Increased movement velocity ($^\circ s^{-1}$) related to increased performance
Endpoint COG excursion	Spatial excursion of postural movements	Contrast of the observed COG excursion against a theoretical maximum	Increased endpoint COG excursion (%) related to increased performance
Directional control	Accuracy of spatial excursions when performing postural movements	Contrast of the observed COG movement in the intended direction, against other erroneous movement	Increased directional control (%) related to increased performance

increases in strategy scores between one and six months post-discharge were noted, these effects being significant for the most perturbed task conditions (Table 2) during conditions five (18.0%) ($p < 0.01$) and six (74.3%) ($p = 0.01$).

Amputees became more able to utilise somatosensory input (Table 2, Fig. 1) to maintain balance between one and six months post discharge (9.7%) ($p < 0.01$). Use of vestibular input (Table 2, Fig. 1) increased by 34.1% during the same timeframe, although this was not statistically significant ($p = 0.07$). Utilisation of visual input (Table 2, Fig. 1) to maintain balance did not change over time ($p = 0.13$) with amputees apparently relying most heavily on visual information, even when inaccurate compared to other sensory inputs. In addition, there was no change in amputees' ability to assess the accuracy of visual information (preference, Table 2, Fig. 1) ($p = 0.21$).

3.2. Limits of stability test

Although there were visible temporal adaptations in participants' reaction time, these effects were mainly non-significant with the exception of a significant increase in the backwards direction between one and six months post-discharge ($p = 0.03$). Fig. 2 illustrates that reaction time was generally greater when moving towards the intact direction than the affected direction at one month post-discharge, with this trend diminishing over time. Although a significant decrease was observed in the affected back direction

Table 3
Group $\bar{x} \pm$ SD equilibrium, strategy and sensory analysis scores from the SOT protocol. Higher equilibrium scores relate to increased balance performance, higher strategy scores relate to increased ankle strategy use and higher sensory analysis scores relate to increased utilisation of sensory input mode.

Equilibrium scores	One¶	Two‡	Three‡	Four	Five‡,§,¶,**	Six‡,§,¶,**	COMP
1 month	92.8 ± 1.4	79.5 ± 7.8*	72.3 ± 21.0*	91.1 ± 0.9*	58.7 ± 26.5	56.4 ± 8.7†,*	72.0 ± 11.4*
3 months	93.1 ± 1.0	83.4 ± 6.0	82.6 ± 8.6	87.2 ± 2.3	69.6 ± 9.6	76.4 ± 6.8†	80.3 ± 3.6
6 months	92.9 ± 1.8	87.3 ± 4.9*	87.0 ± 4.8*	88.7 ± 2.3*	76.1 ± 6.7	74.8 ± 7.8*	83.1 ± 2.9*

Strategy Scores	One	Two	Three	Four	Five‡,§,¶,**	Six‡,§,¶,**
1 month	93.4 ± 2.5	79.3 ± 15.7	74.0 ± 21.3	86.5 ± 2.2	61.8 ± 14.6*	40.5 ± 15.†,*
3 months	94.6 ± 1.9	86.7 ± 8.1	84.2 ± 11.5	85.9 ± 3.5	66.6 ± 17.1	69.8 ± 13.7†
6 months	92.6 ± 4.8	87.4 ± 7.1	89.9 ± 4.1	86.5 ± 1.9	72.9 ± 8.7*	70.6 ± 13.1*

Sensory analysis	Somatosensory	Visual	Vestibular	Preference
1 month	85.7 ± 7.7*	98.2 ± 1.8	60.9 ± 29.2	93.7 ± 12.0
3 months	89.6 ± 6.2	93.7 ± 2.9	73.6 ± 10.3	104.6 ± 11.6
6 months	94.0 ± 4.6*	95.5 ± 3.6	81.7 ± 7.4	99.3 ± 8.4

††Significant compared to condition five. ‡‡Significant compared to condition six.
* Significant between one and six months.
† Significant between one and three months.
‡ Significant compared to condition one.
§ Significant compared to condition two.
¶ Significant compared to condition three.
** Significant compared to condition four.

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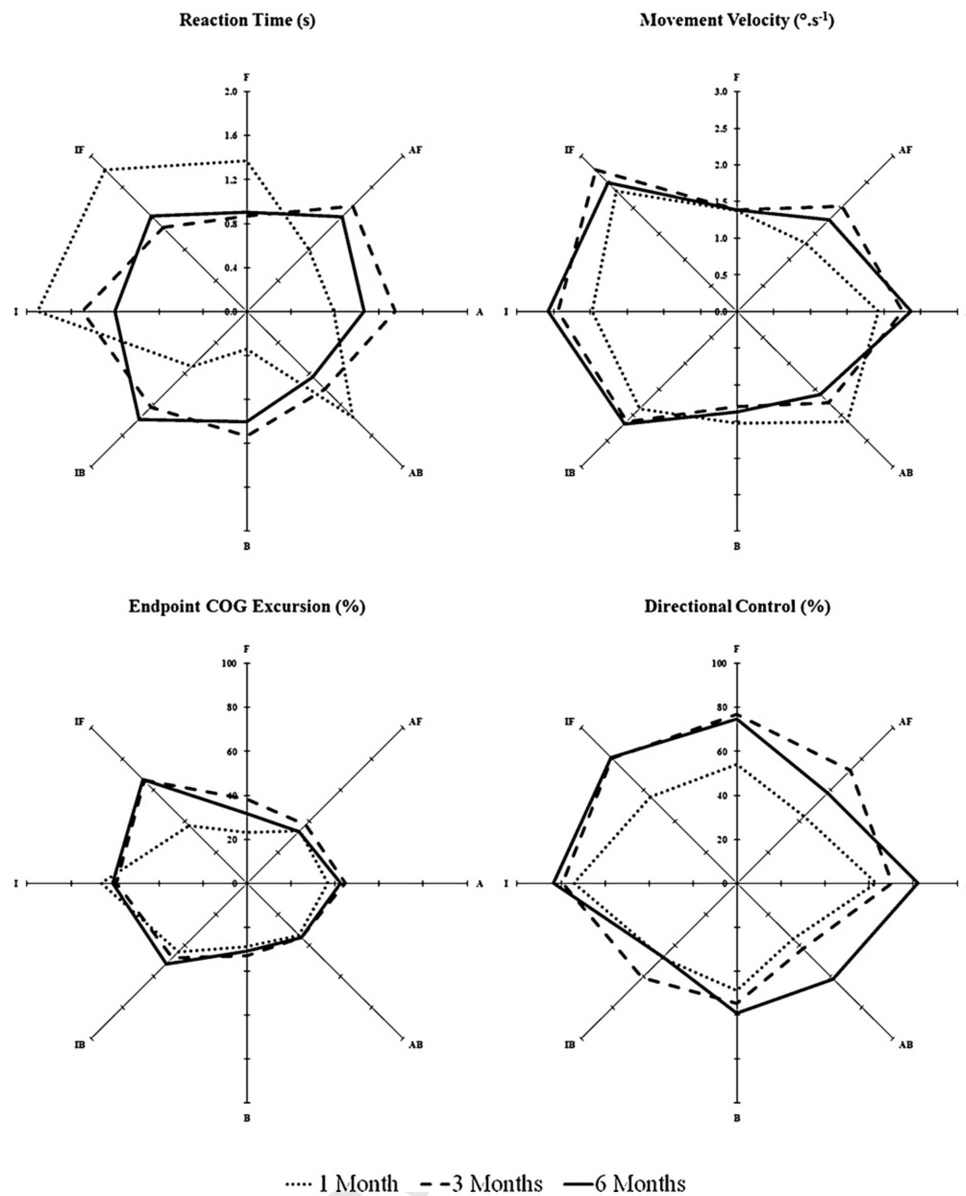

Fig. 2. Target plots of group $\bar{x}$ scores from LOS test protocol. A – affected limb direction, I – intact limb direction, F – forward direction and B – backward direction. Scores closer to outer border indicate increased performance with the exception of reaction time where scores closer to centre indicate increased performance.

between one and six month post discharge ($p < 0.05$), changes in movement velocity were variable over time suggesting that participants were not able to modulate the speed at which postural adjustments were performed. Endpoint COG excursion increased significantly in the intact forward direction between one and three months (77.2%) ($p = 0.02$) and between one and six months (78.8%) ($p = 0.02$) post-discharge. Fig. 2 illustrates that participants were better able to explore their LOS on the intact side, especially with the addition of an anterior (intact forward) or posterior (intact back) component. Fig. 2 highlights increases in the accuracy of postural movements, inferred from directional control scores, with the exception of intact and intact back directions. These increases were statistically significant improvements in affected forward ($p = 0.04$), intact forward (one and three months $p = 0.02$, one and six months $p < 0.01$) and back (one and three months $p < 0.01$) directions.

4. Discussion

The aim of the current study was to assess postural adaptations in transtibial amputees following discharge from rehabilitation. Results suggested that participants' balance ability in response to dynamic perturbations was improved at six months following discharge from rehabilitation, with the greatest improvement occurring during the most perturbed conditions. However, contrasted against results from amputees with more prosthetic experience, the balance ability of the current group was reduced in all conditions of the SOT test protocol [10]. This suggested that even greater future improvements may be anticipated or induced during balance tasks incorporating perturbed sensory environments [10]. The lack of significant improvement during static conditions and increased A–P sway during more challenging conditions suggested that amputee rehabilitation protocols should consider the inclusion of practising balance tasks whereby balance is dynamically perturbed. These highly challenging task conditions may elicit further or more rapid increases in overall balance ability and may include balance whilst on uneven or varied terrain (e.g. wobble board) and on surfaces with varying materials and densities.

Supporting previous findings, there was an increased use of the ankle strategy during less perturbed task conditions, with

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increasing hip strategy use as task difficulty increased [10]. Also, reductions in reliance on the hip strategy during more dynamic task conditions over time were observed. When compared to more experienced prosthetic users [10], strategy scores in the current study were reduced in all SOT conditions, except conditions four and five which were similar. This suggests that recent amputees rely on a combination of ankle and hip strategies during more complex conditions. Therefore, a reduced reliance on the hip strategy and an increased utilisation of the ankle strategy in recent transtibial amputees, particularly during dynamic balance, may be expected over time, as reported in more experienced amputees [10]. Future balance training or prosthetic prescription should be mindful of the prosthetic ankle joint function in order to improve overall balance ability, with reports suggesting that amputees may ease control of the lower limb during balance tasks by using the more rigid prosthetic ankle mechanism [15].

The use of the ankle strategy during condition four, where accurate visual information was provided during support surface perturbation (inaccurate somatosensory information), did not change significantly over time. This suggests that participants may have prioritised accurate visual information over the perturbed somatosensory information, which is supported by the suggestion that in unusual sensory environments, the most reliable source of sensory information is selected [1].

The results supported the notion that amputees rely heavily upon visual information during both static [7] and dynamic balance conditions [10]. This trend did not change over time suggesting this was a fairly well established characteristic of transtibial amputee balance ability. However, there was a significant increase in somatosensory input use over time, which may have contributed to the overall increase in balance performance. Given that previous literature has suggested that transtibial amputees utilised board-floor contact as an additional source of sensory input during a dynamic balance task [8], it may be hypothesised that overall increases in the use of somatosensory input originated, in part, from the affected limb, as recent amputees adapted to the altered somatosensory sensory input available from this limb [4]. Nonetheless, when compared to amputee non-fallers during a dynamic translator balance task, amputee fallers have been shown to weight-bear more on the affected limb than the intact limb [10]. These findings suggest that the development of balance ability may be achieved by safely increasing an amputee's ability in utilising somatosensory input, without increasing falls risk [4]. However, this suggestion must be made with caution as the current test protocols were not able to establish the precise location of increased somatosensory input. In addition, it is important to consider the interaction of somatosensory input with other available sensory information (e.g. visual and vestibular), as well as muscle strength and joint mobility, in the improvement of balance ability. These cautionary considerations should be integrated into the design of future research.

Few significant longitudinal adaptations were noted for reaction time and movement velocity, and this may have reflected participants' reluctance or inability to initiate or perform movements quickly due to decreased afferent somatosensory input or fear of falling [11]. When volitionally required to stress the postural control system, participants did not modulate the temporal aspects of postural control which is a novel finding, as balance ability during external perturbations assessed via the SOT displayed longitudinal improvements. However, movement velocity was generally faster in the M–L direction than the A–P direction. This may have reflected a number of effects including participants' unwillingness to lean forwards or backwards quickly, reduced theoretical M–L limits of stability negating postural control requirements, increased fear of falling in the A–P direction, relative lower limb muscle strength controlling M–L movement or prosthetic fitting. The mechanisms of these effects are unknown and would benefit from further investigation.

Significant adaptations in postural control were noted from both a spatial and accuracy perspective, previously unreported in recent transtibial amputees. Directional control and endpoint COG excursion improved significantly in a number of directions suggesting that there was an interaction in the volitional exploration of participants' LOS. Participants' reluctance in modulating the temporal aspects of postural control whilst increasing the magnitude and accuracy of postural movements hinted at a trade-off between these aspects of postural control. It could be hypothesised that with greater experience or practice, the temporal aspects of postural control may improve.

Participants in the current study displayed reduced COG excursion when leaning towards the affected limb in comparison to the intact limb. Increased sway has been associated with the affected limb when compared to the intact limb [7] whilst assessment made with the SOT protocol reported that amputee non-fallers have relied more upon the intact limb to maintain balance [10]. These reports, albeit employing differing protocols and subsequent amputee postural control strategies, coupled with the observed affected limb adaptations reported in the current study, may have important implications for transtibial amputee postural control. It could be hypothesised that the level of postural control associated with affected limb necessitates the use of the intact limb in successful postural control. However, everyday circumstances may require affected limb use during balance tasks beyond amputees' preferred volitional level. It could be suggested that activities that practice the volitional use of the affected limb during postural control tasks may be beneficial, given that postural sway reduces during rehabilitation [6]. There are contemporary low cost tools such as the Nintendo Wii™ utilising similar COG excursion assessments as seen in the current LOS test protocol, that have been reported to increase balance function in clinical populations [16,17]. Future research should focus upon quantifying the effect of these interventions in representative transtibial amputee populations across timeframes spanning the rehabilitation process and immediately following discharge from rehabilitation. In addition, the impact of these interventions on subsequent falls rate, balance confidence and quality of life, among other variables, would be of use to clinicians involved in the care of transtibial amputees.

5. Conclusion

Balance ability during dynamic and sensory perturbations improved in the time period following discharge from rehabilitation in unilateral transtibial amputees. However, these individuals were heavily reliant upon vision in order to maintain balance. Decreased reliance upon the hip strategy along with increased use of somatosensory input, may have explained the improvements in overall balance function. Following discharge from rehabilitation, amputees were seemingly able to increase the spatial and accuracy aspects of volitional exploration of their LOS. However, temporal aspects did not display any adaptation suggesting a trade-off between these aspects of postural control. It could be suggested that further practice of balance ability and postural control should focus upon improving affected limb function. Performing volitional postural movements under increasing time pressure may also improve postural control in terms of amputees' ability to react and respond to unexpected perturbations.

Conflict of interest

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

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