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Original Research

Vibration Sensitivity Is Associated With Functional Balance After Unilateral Transtibial Amputation

Mayank Seth, PhD [a], Emma H. Beisheim-Ryan, PT, DPT, PhD [a], Ryan T. Pohlig, PhD [b], John Robert Horne, CPO [c], Gregory E. Hicks, PT, PhD, FAPTA [d], Jaclyn M. Sions, PT, DPT, PhD [a]

[a] *Delaware Limb Loss Studies, Department of Physical Therapy, University of Delaware, Newark DE*
[b] *Biostatistics Core, University of Delaware, Newark, DE*
[c] *Independence Prosthetics-Orthotics, Inc, Newark, DE*
[d] *Delaware Spine Studies, Department of Physical Therapy, University of Delaware, Newark DE*

KEYWORDS
Amputation;
Lower extremity;
Perception;
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Prostheses and implants;
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Vibration

Abstract *Objectives:* To evaluate differences in vibration perception thresholds between adults with transtibial amputation and age-matched adults without amputation and to examine associations between vibration perception thresholds and balance performance. We hypothesized that adults with transtibial amputation would demonstrate lower thresholds compared with adults without amputation and that lower thresholds would be associated with better functional balance.
Design: Prospective cross-sectional study.
Setting: National conference, clinical practice, and university laboratory.
Participants: Adults (N=34) with a nondysvascular, unilateral, transtibial amputation and 43 age-matched controls without amputation.
Interventions: Participants' vibration perception thresholds were evaluated bilaterally by applying a vibration stimulus to the midpatella and recording their verbal response to conscious

List of abbreviations: BBS, Berg Balance Scale; FSST, Four Square Step Test; ICC, intraclass correlation coefficient; LLA, lower-limb amputation; TTA, transtibial amputation; VPT, vibration perception threshold.

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perception of stimulus. Functional balance was assessed with the Berg Balance Scale and the Four Square Step Test.
Main Outcome Measures: Residual and sound limb (right and left for controls) vibration perception thresholds, Berg Balance Scale, and Four Square Step Test.
Results: For participants with transtibial amputation and controls, there were no significant between-group (P=.921) or interlimb (P=.540) differences in vibration perception thresholds. Overall, robust regression models explained 35.1% and 19.3% variance in Berg Balance Scale scores and Four Square Step Test times, respectively. Among adults with transtibial amputation, vibration perception thresholds were negatively associated with Berg Balance Scale scores (P=.009) and positively associated with Four Square Step Test times (P=.048). Among controls, average vibration perception thresholds were not significantly associated with functional balance (P>.050).
Conclusions: Adults with nondysvascular, transtibial-level amputation demonstrated similar vibration detection compared with adults with intact limbs, indicating that vibration detection is preserved in the amputated region postamputation. These findings suggest a unique relationship between vibration perception and functional balance post-transtibial amputation.

Somatosensory feedback from the feet plays a vital role in the maintenance of balance and movement control.[1] Plantar cutaneous afferents relay changes in external stimuli, including pressure, stretch, and vibration to the central nervous system,[2] thereby aiding in postural control.[3] After a lower-limb amputation (LLA), the loss of a foot may severely diminish sensory input to the central nervous system. Under such circumstances, the residual limb (ie, portion remaining after amputating) may serve as a proxy to the anatomic foot. Currently, however, research regarding the residual limb's sensitivity to sensory stimuli (eg, vibration) is sparse. Reduced residual limb sensitivity (ie, higher thresholds for detecting sensory stimuli) has been reported among adults with transtibial amputation (TTA) resulting from dysvascular etiologies (eg, diabetes, peripheral vascular disease) [4]; however, vascular conditions can reduce cutaneous sensitivity,[5] making it difficult to disentangle losses in cutaneous sensitivity as a result of LLA from pathologic reductions in sensitivity secondary to dysvascularity.

Cortical reorganization may result from sensorimotor network changes post-LLA.[6,7] Functional magnetic resonance imaging of the brain demonstrates significantly higher activity in the contralateral sensorimotor cortex of adults with traumatic LLA after residual limb stimulation (3-5 Hz) compared with controls without amputation.[6,7] Bramati et al suggest that higher cortical activity post-LLA may be the result of disinhibition of neural activity in the somatosensory pathways, causing residual limb stimulation to activate more cortical areas compared with stimulation of a homologous location in adults without amputation.[6] Based on this hypothesis, the residual limb may have a broader sensory map, which may allow heightened sensitivity, or sensory stimuli detection at lower thresholds.

Somatosensory feedback perceived through cutaneous mechanoreceptors, particularly vibration perception,[8] is critical for both static and dynamic balance.[9] The significance of vibration perception is also evidenced by studies involving the experimental manipulation of vibratory stimuli; for example, application of subthreshold vibration to the plantar surface of the feet has been shown to reduce postural sway in healthy adults.[10]

Vibration perception post-LLA remains relatively unexplored, but some evidence suggests impaired vibration detection as a unique risk factor for falls post-LLA.[4] Although prior research suggests enhanced perception post-LLA,[6] adults with a major LLA (eg, TTA) who use a prosthesis may experience attenuated somatosensory feedback at the residual limb. Given that somatosensory feedback is received via prosthesis (ie, secondary) and the limb is encased by a liner or socks, overall feedback may be diminished, possibly explaining impaired static and dynamic balance[11,12] and increased fall risk.[13] Certain performance-based outcome-measures (eg, Berg Balance Scale [BBS], Four Square Step Test [FSST]), capture the ability to maintain static and dynamic balance via functional tasks (eg, reaching, stepping over objects), and as such evaluate functional balance and may be predictive of fall risk.[14,15]

Hence, the objectives of this study were to (1) evaluate interlimb differences in vibration perception among adults with nondysvascular TTA without phantom (or residual) limb pain, (2) compare vibration perception with age-matched controls without amputation, and (3) evaluate associations between vibration perception and functional balance among adults post-TTA compared with age-matched controls. We hypothesized that adults post-TTA would have lower vibration perception thresholds (better detection) in their residual limb (compared with their sound limb), and compared with age-matched controls without amputation, and that lower vibration perception thresholds would be associated with better functional balance.

Methods

Participants

Participants for this cross-sectional research study were recruited from January 2018 to November 2020 via advertisements through Amputee Coalition National Conferences; local support groups for individuals with limb loss; and prosthetic, rehabilitative, and physiatry practices.

Databases of individuals with LLA who requested to be contacted for research conducted by the Delaware Limb Loss Studies were also used. Adults post-TTA and age-matched controls were included if they were at least 18 years old, English-speaking and -reading, and did not have a systemic neuromuscular disease (eg, Parkinson Disease). For adults post-TTA, additional inclusion criteria included unilateral TTA at least 1 year prior and use of a definitive prosthesis for at least 8 hours per day. Exclusion criteria included TTA owing to vascular etiology (ie, diabetes, peripheral vascular disease), contralateral toe amputations (or greater "sound-limb" involvement), use of an assistive device greater than a cane for ambulation, phantom limb pain (ie, pain perceived as coming from the amputated limb), residual limb pain (ie, pain in the remaining limb of the amputated side), or a current condition of the residual limb precluding safe participation (eg, ulceration). Controls who reported pain, numbness, or tingling in their lower limbs were excluded. The Institutional Review Board for Human Subjects Research at the University of Delaware (project no. 1094323; initial approval no. 12/13/2017) approved this project.

Procedures

Participants underwent informed consent process and signed an institutional review board—approved consent form. All participants provided basic demographic information including sex, age, height, and weight, and completed physical function (test-retest reliability: intraclass correlation coefficient $[ICC]_{3,1}$=0.90) and participation (test-retest reliability: $ICC_{3,1}$=0.75) domains of the 29-item Patient-Reported Outcomes Measurement Information System.[16] Participants post-TTA provided amputation-specific information, completed the Houghton Scale (test-retest reliability: $ICC_{2,1}$=0.96),[17] and reported their socket comfort score (test-retest reliability: $ICC_{3,1}$=0.77).[16] Vibration perception of both lower limbs was assessed and performance-based outcomes evaluating functional balance were administered.

Outcome measures

The BBS assesses static and dynamic balance through 14 functional tasks scored on an ordinal scale ranging from 0 to 4, with higher scores indicating better balance.[18] Interrater reliability ($ICC_{2,1}$=0.95) and convergent validity for adults post-LLA has been reported previously.[18]

The FSST assesses dynamic balance through multidirectional stepping.[19] Participants complete a sequence of steps over 4 canes arranged in a "+" as fast as safely possible without touching the canes (fig 1).[20] After demonstration, participants completed 1 practice and 2 timed trials (recorded in seconds, without examiner cueing for sequencing to avoid participant pacing). Touching canes or incorrect sequencing constituted an invalid trial; the best time of 2 trials was used for analyses. FSST test-retest reliability ($ICC_{2,1}$=0.97) for adults post-LLA has been reported previously.[21]

Vibration testing protocol

Vibration detection was assessed with the Vibratron II,[a] which has been used previously for assessing vibration sensitivity.[22-24] Test-retest reliability has been reported in various populations, including adults with low back pain[25] and diabetes.[26] The Vibratron II includes a controller and a vibrating transducer (120Hz) with a 1-cm post. The control unit allows vibration amplitude modulation from 0.0 to 20.0 vibration units (0.1 vibration unit=0.005 microns; 20.0 vibration units=200 microns). Vibration stimulus was applied at midpatella, a bony landmark easily determined for all study participants. Testing order was randomized between limbs.

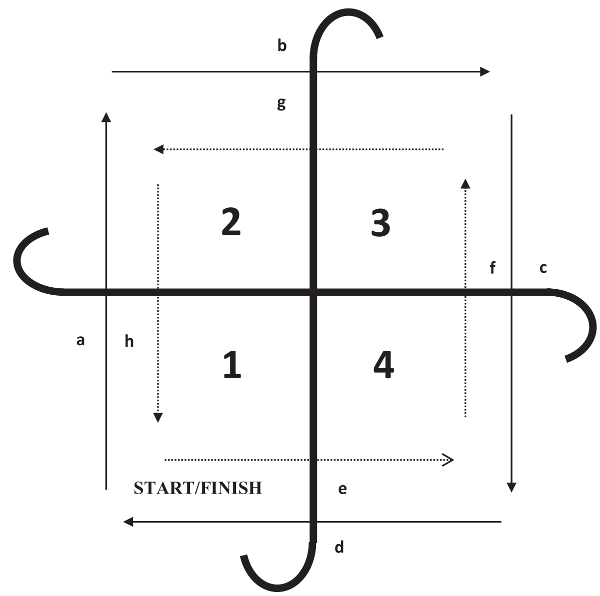

Fig 1 Course layout for the FSST. Participants start in square 1 and move clockwise to square 1 (a-d) and then reverse (move counterclockwise) and return to square 1 (e-h). Each foot must make contact with each square for a valid timed trial.

Participants were familiarized with the vibration stimulus and testing protocol through application to the index finger prior to lower-limb testing. For midpatella testing, the transducer was applied by a trained examiner while another examiner modulated vibration amplitude via the control unit. Vibration sensitivity was assessed using the methods of limits procedure, involving 5 descending and 4 ascending trials.[27] During descending trials, a suprathreshold stimulus (20 vibration units) was delivered to the patella, and gradually reduced (by ~0.1 vibration unit) until the participants verbalized that they could no longer detect the stimulus. During ascending trials, a subthreshold stimulus was delivered and gradually increased (by ~0.1 vibration unit) until the participant first verbalized detection of the vibration. Vibration units corresponding to the participant's response were recorded for each trial. The weighted average of 9 trials was used to quantify vibration perception threshold (VPT) for each limb. Participants wore noise-reducing headphones during testing to reduce background noise and enhance attention to procedure. As test-retest reliability for assessing vibration detection among adults post-TTA at the midpatella using the Vibratron II is unpublished, a subset of participants (n=11) underwent vibration testing on 2 occasions separated by 1 to 7 days.

Statistics

Analyses were conducted using SPSS Statistics, version 26.[b] Between-days test-retest reliability for vibration assessment using the Vibratron II was evaluated using ICC with a 2-way, mixed effects model (3, k).[28] Between-group differences for demographics and balance were examined using chi-square, Mann-Whitney *U*, and independent samples *t* tests, as appropriate. A 2 $\times$ 2 mixed design analysis of covariance compared VPT between groups (TTA vs control) and between limbs (residual vs sound and right vs left, respectively), while adjusting for age. The effect of group (TTA vs control), VPT, and their interaction with functional balance (ie, BBS and FSST) was tested using robust regression with HC3 standard errors. Robust standard errors were used given observed non-normality and presence of potential outliers. Significance for each planned comparison was set at 0.05.

Results

Participants

Overall, 285 adults were contacted, of whom 234 were post-LLA and 51 were adults without LLA (fig 2). Of the 234 adults post-LLA contacted for participation, 64 could not be reached or were not interested; 130 were ineligible based on study criteria. Of the 40 adults with TTA who were eligible for the study, 34 fully completed the study protocol (6 did not and were excluded from analyses). Of the 51

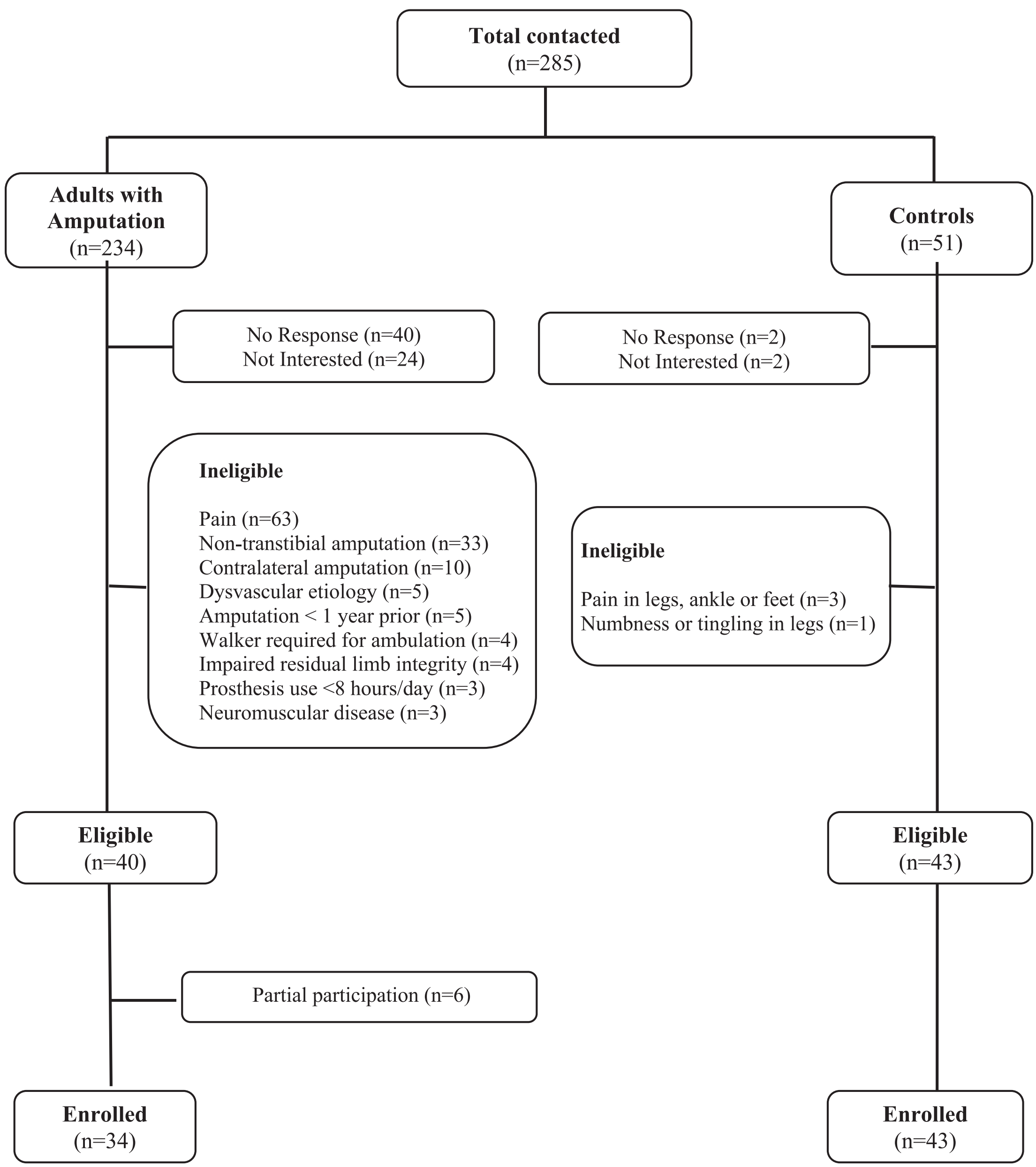

Fig 2 Participant selection based on exclusion and inclusion criteria.

Table 1 Participant demographics

Characteristic	TTA (n=34)			Controls (n=43)			*P* Value
Female sex, n (%)	12 (35.3)			22 (51.2)			.176
Age, y	49.3 (15.0)			49.2 (15.2)			.975
BMI, kg/m^2	29.0 (5.0)			28.0 (5.0)			.389
Amputation etiology, n (%)							
Trauma	16 (47.1)						
Cancer	1 (2.9)						
Congenital	2 (5.9)						
Infection	9 (26.5)						
Other	6 (17.6)						
TSAmp, median (25th, 75th percentile), y	6 (2, 25)			-			-
Houghton scale, median (25th, 75th percentile), 0-12*	12 (11, 12)			-			-
Socket comfort score, median (25th, 75th percentile), 0-10†	9 (8, 10)			-			-
PROMIS-29	T-score			T-score			
Physical function, median (25th, 75th percentile), 22.9-56.9‡	56.9 (48.0, 56.9)			56.9 (56.9, 56.9)			.002
Ability to participate in social roles and activities, (25th, 75th percentile), 27.5-64.2§	64.2 (53.7, 64.2)			64.2 (64.2, 64.2)			.123
Comorbidities	**Yes**	**No**	**Total valid cases**	**Yes**	**No**	**Total valid cases**	
Heart disease	2	32	34	1	40	41	.587
Osteoarthritis	1	33	34	1	42	43	>.99
Numbness or tingling	4	30	34	1	41	42	.167

Abbreviations: BMI, body mass index; PROMIS-29, Patient-Reported Outcomes Measurement Information System-29 item; TSAmp, time since amputation.

* Measures prosthesis use and stability when wearing a prosthesis.

† Participants rated socket comfort from 0 (most uncomfortable) to 10 (most comfortable) at the time of evaluation.

‡ Measures physical function on 4 items (chores, stair climbing, walking for 15 minutes, and running errands) that are each scored from 1 (unable to do) to 5 (without difficulty) and summed for a raw score that is converted to a T-score, where 50 represents the mean of the reference sample.

§ Measures participation on 4 items (regular leisure activities, family activities, usual work, and activities with friends) that are each scored from 1 (always) to 5 (never) and summed for a raw score that is converted to a T-score, where 50 represents the mean of the reference sample.

individuals contacted to serve as age-matched controls, 43 were eligible and enrolled. Participant characteristics are presented in table 1. The median time since amputation and Houghton Scale score indicate that the participants with TTA were long-term prosthesis users and independent community ambulators.[29] Sample median Patient-Reported Outcomes Measurement Information System-29 scores suggest high physical function and participation.

Reliability results

For both limbs, the Vibratron II demonstrated good[30] between-days test-retest reliability (residual limb: $ICC_{(3,k)}$=0.886; 95% CI, 0.582-0.969; sound limb: $ICC_{(3,k)}$=0.828; 95% CI=0.301-0.955) for measuring VPT at the patella of adults with TTA.

Main results

VPT (see table 2) was not significantly different between participants with TTA and controls [F(1.74)=0.01; *P*=.921; η^2=0.00]. Moreover, there was no main effect of limb [F (1.74)=0.38; *P*=.540; η^2=0.01]; no inter-limb (residual vs sound, right vs left) differences were observed. Age was significantly related to VPT, while adjusting for group and limb [F(1.74)=13.57; *P*≤.001; η^2=0.16].

Participants post-TTA had significantly different BBS scores (*P*=.009) and FSST times (*P*=.010) compared with controls (see table 2). Based on mean ranks, it is likely that a greater number of adults with TTA had lower BBS scores and higher FSST times (see table 2). Given that no interlimb differences were observed, right-left average VPT was used when examining the effect of group and VPT on functional balance. Overall, the models explained 35.1% and 19.3% of the variance in BBS and FSST, respectively. In both models, participants with TTA demonstrated a significant association between average VPT and functional balance (BBS: TTA × VPT; *P*=.009; FSST: TTA × VPT; *P*=.048; see table 3), such that, a 1-vibration unit increase in average VPT may be associated with a 0.75-point decrease in BBS score and a 0.51 second increase in FSST time. For controls, VPT was not associated with functional balance (BBS: control × VPT; *P*=.207; FSST: control × VPT; *P*=.537; see table 3).

Table 2 Vibration perception thresholds and balance performance of participants with TTA and controls

	TTA (n=34)			Controls (n=43)			*P* Value
	Vibration Perception Thresholds						
Limb	Mean ± SD		Total Valid Cases	Mean ± SD		Total Valid Cases	
Residual limb (or right)	10.0±2.8		34	10.4±3.2		43	.540*
Sound limb (or left)	10.5±3.4		34	10.9±3.1		43	
	Balance Performance						
Measures	Median (25th, 75th Percentile)	Mean Rank	Total Valid Cases	Median (25th, 75th Percentile)	Mean Rank	Total Valid Cases	
BBS, 0-56	56 (53, 56)	33.26	34	56 (56, 56)	43.53	43	.009
FSST, s†	8.93 (8.16, 10.19)	45.13	31	8.03 (6.94, 8.94)	32.00	43	.010

NOTE. Weighted averages were used to compute vibration perception thresholds for each limb, given that 5 descending and 4 ascending vibration trials were conducted.
* Indicates main effect of limb
† Three participants had no valid trials.

Table 3 Robust regression results

Parameter	b*	Robust Standard Error	*P* Value	b*	Robust Standard Error	*P* Value
		BBS			FSST	
Intercept	61.087	2.727	≤.001	4.359	2.326	.065
control × VPT†	−0.049	0.039	.207	0.073	0.118	.537
TTA × VPT†	−0.746	0.279	.009	0.510	0.254	.048
Group‡	−4.818	2.749	.084	3.014	2.628	.255
R^2§	0.351		≤.001	0.193		.002

* b refers to unstandardized beta coefficients.
† VPT represents the right-left or residual-sound average vibration perception threshold.
‡ Group was coded as 0 (control) and 1 (TTA); reference group for analysis was TTA.
§ R^2 refers to overall variance explained by model.

Discussion

After LLA, the residual limb may serve as a surrogate to the anatomic (amputated) foot, receiving sensory information to maintain postural control. Our findings indicate similar vibration perception between residual and sound limbs of adults with unilateral, nondysvascular TTA, and that vibration perception is similar to that of adults with intact limbs. This is clinically relevant, suggesting preservation of vibration detection in the residual limb postamputation, pending absence of dysvascularity and pain. Among adults post-TTA, vibration perception is significantly associated with functional balance, in that lower VPT (ie, better detection) is associated with higher BBS scores and shorter FSST times. Findings suggest vibration perception as a unique factor in functional balance post-TTA, as vibration perception was not associated with functional balance among age-matched adults with intact limbs. Future interventions, including advancements in prosthetic technology, may capitalize on intact vibratory perception postamputation as a means of enhancing functional balance and reducing fall risk.

Cortical reorganization at the sensorimotor cortex of adults with traumatic LLA (without phantom limb pain) suggests expansion of the residual limb's sensory map, which may enhance residual limb sensitivity.[6] Our findings among a subgroup of adults post-TTA (nondysvascular etiology without phantom or residual limb pain), however, fail to support heightened limb sensitivity, as vibration perception thresholds were similar between residual and sound limb post-TTA and comparable to age-matched participants without limb loss. Perhaps our findings are secondary to the use of sensory stimuli required for conscious perception or verbalization of perception, compared with low or subliminal stimulation that has been shown to elicit cortical activity per brain imaging.[31] Hence, postamputation, conscious awareness of vibration may require greater vibratory stimuli (that is similar to adults without LLA), and thus, our protocol may be unable to signify cortical reorganization postamputation.

Compared with adults with intact limbs, Templeton et al reported lower thresholds for vibration perception (40 and 250 Hz) at bilateral lower-limb sites for a participant with traumatic-TTA experiencing daily phantom limb pain.[32] Given generalized hyperalgesia associated with phantom limb pain[33] and pain, in general,[34-36] adults with phantom limb pain may have heightened cutaneous sensitivity and hence, lower vibration perception thresholds (better detection) when compared with pain-free individuals postamputation. Another potential explanation for differing findings may be vibration frequency (as we used 120Hz). Although Pacinian corpuscles (ie, mechanoreceptors) primarily responding to vibration stimuli have a frequency response range of 20 to 1000 Hz,[37] it remains unclear whether thresholds for vibration detection are frequency specific.

Cutaneous sensitivity to somatosensory stimuli is an important consideration for static and dynamic balance maintenance.[9] Cutaneous vibration sensitivity, in particular, may be critical to balance maintenance.[4,8] Our findings align with previous evidence and indicate a unique relationship between vibration perception post-TTA and balance performance (compared with controls). Specifically, post-TTA, a 1-vibration unit increase in VPT (ie, reduced sensitivity) may be associated with 0.75-point decrease in BBS and a 0.51-second increase in FSST. Among controls, however, vibration perception was not associated with functional balance. We acknowledge that our ability to detect a significant association may have been reduced given the BBS appears to demonstrate a ceiling effect among our control participants (see table 2). If, however, an association between vibration perception and functional balance were present in controls (see table 3), we might expect to also see a correlation between vibration perception and the FSST (which did not demonstrate a ceiling effect).

Differences between the 2 groups may be rooted in the mechanisms used for somatosensory feedback. Adults without amputation primarily rely on their anatomic feet for somatosensory feedback, as the organization of receptors in the glabrous skin on the plantar surface of the foot (ie, high proportion of fast-adapting receptors,[38] high receptor density under the toes and lateral border of the foot[5,39]) makes it well-suited for postural control. In contrast, the hairy skin over the midpatella (composed of largely slow-adapting receptors) is less sensitive to tactile stimuli.[38] Hence, vibration perception in the midpatella region, as measured in this study, may not have any bearing on functional balance ability in controls. In contrast, for adults with TTA, the residual limb is the primary source for somatosensory feedback and vibration perception at the midpatella region may have more relevance for functional balance post-TTA.

The residual limb post-TTA may be disadvantaged given encasement within a socket, liner, or socks, resulting in attenuation of indirect sensory feedback from the prosthetic foot. Hence, even though adults post-TTA may have intact sensation, sensory feedback may be limited, possibly explaining the greater proportion of adults post-TTA demonstrating worse functional balance outcomes compared with age-matched controls (see table 2).

Considering our findings, it may be vital to enhance residual limb vibration sensitivity post-TTA to promote better functional balance outcomes. For example, Rusaw et al examined balance outcomes among adults post-TTA (n=24) receiving real-time vibratory feedback (proportional to somatosensory feedback from under the prosthetic feet via force sensors) at the thigh (outside prosthesis) of their residual limb.[40] With vibratory feedback, there were significant increases in mediolateral center of pressure excursions (ie, individuals could move their bodies further without losing balance) and reductions in response time during limits of stability testing, suggesting overall better postural control.[40] Alternatively, residual limb somatosensory feedback may be augmented through stochastic resonance, where cutaneous application of subthreshold vibration (noise) is used to improve perception of weak stimuli. Specifically, Likens et al applied subthreshold vibration to the residual limb thigh among adults post-TTA (n=20), reducing postural sway and gait variability.[41] Although currently experimental, the use of vibratory technologies may provide augmented somatosensory feedback to overcome loss of the anatomic foot, and the environment inherent to the prosthesis-limb interface, to enhance functional balance post-TTA, particularly because vibratory thresholds appear to be preserved postamputation, in the absence of dysvascularity and pain.

Study limitations

Results may only be generalized to pain-free community-ambulating adults who are at least 1-year postamputation secondary to a nondysvascular TTA, and who are using a traditional socket-suspension prosthesis (ie, not an osseointegrated implant). Our lack of details on participant residual limb length and prosthesis system (eg, socket-type, suspension system or liner), however, precludes our ability to discuss the effect, if any, of residual limb length and prosthesis componentry on vibration perception. Vibration perception should be considered specific to the patella or knee region and may not be applicable to more proximal locations on the lower limbs. Future research may evaluate potential somatosensory feedback dampening at the prosthesis-limb interface, which may improve future prosthetic innovation targeting preserved or enhanced somatosensory feedback from the residual limb. Moreover, to better understand the effect of residual limb vibration perception on balance, future research may consider controlling for factors known to affect vibration perception and balance. As vibration perception was only evaluated at 120 Hz, future studies may consider replicating our methodology at other frequencies. Lastly, future work may consider use of an apparatus to stringently control pressure applied to the patella during vibration application, although test-retest reliability was good (ICC point estimates >.750) for our methodology.

Conclusions

Adults with nondysvascular TTA without phantom or residual limb pain demonstrated similar vibration perception bilaterally, with thresholds comparable to those of age-matched controls with intact limbs. Among adults with TTA, but not age-matched controls, vibration perception at the patella was associated with functional balance. Specifically, adults with better vibration detection had better functional balance, as evaluated with the BBS and FSST. Hence, vibration perception may have a unique relationship with functional balance post-TTA. Given the loss of sensory input from the amputated foot and potential dampening of sensory feedback due to prosthetic liners and socks, augmenting vibratory feedback at the residual limb may be vital to improving balance outcomes post-TTA.

Suppliers

a. Vibratron II; Physitemp Instruments, LLC.
b. SPSS Statistics for Windows, version 26.0; IBM Corp.

Corresponding author

Mayank Seth, PhD, 540 South College Avenue, Suite 144A, University of Delaware, Newark, DE, 19713. *E-mail address:* mseth@udel.edu.

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