Gait & Posture 39 (2014) 672–682

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Review

Balance control in lower extremity amputees during quiet standing: A systematic review

Pei Xuan Ku *, Noor Azuan Abu Osman [1], Wan Abu Bakar Wan Abas [2]

Department of Biomedical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

ARTICLE INFO

Article history:
Received 4 April 2013
Received in revised form 2 July 2013
Accepted 4 July 2013

Keywords:
Postural balance
Centre of pressure
Amputation
Standing posture
Sway

ABSTRACT

Postural control has been widely evaluated for the normal population and different groups over the past 20 years. Numerous studies have investigated postural control in quiet standing posture among amputees. However, a comprehensive analysis is lacking on the possible contributing factors to balance. The present systematic review highlights the current findings on variables that contribute to balance instability for lower extremity amputees.

The search strategy was performed on PubMed, Web of Science, Medline, Scopus, and CINAHL and then followed by additional manual searching via reference lists in the reviewed articles. The quality of the articles was evaluated using a methodological quality assessment tool. This review included and evaluated a total of 23 full-text articles.

Despite the inconsistencies in the methodological design of the studies, all articles scored above the acceptable level in terms of quality. A majority of the studies revealed that lower extremity amputees have increased postural sway in the standing posture. Asymmetry in body weight, which is mainly distributed in the non-amputated leg, was described. Aside from the centre of pressure in postural control, sensory inputs may be a related topic for investigation in view of evidence on their contribution, particularly visual input. Other balance-related factors, such as stump length and patients' confidence level, were also neglected. Further research requires examination on the potential factors that affect postural control as the information of standing postural is still limited.

1. Introduction

Postural balance, which refers to the essential ability of maintaining daily functions and involving in sports activities, has become one of the major concerns among the society. Balance can be defined as the ability to regain the centre of mass (CoM) within the base of support to maintain body equilibrium. The CoM reflects the centre of body location movement and changes accordingly to preserve balance. It also serves as an important factor in lower extremity amputation (LEA) where balance impairment may increases the risk of falling. In 2007, an estimated 1.7 million people were reported to have lost limbs (excluding fingers) in the United States. A trend of increasing hospital costs is associated with amputation incidences.

Several reasons lead to amputation, such as vascular diseases and peripheral arterial diseases. Diabetes patients have 10–30 times greater lifetime risk of undergoing LEA compared with the general population [1]. About 20–50% of diabetes amputees will require second leg amputation within one to three years, and more than 50% of the amputees will need amputation within five years [2]. Due to the missing limb in the lower extremity, the range of displacement is affected, and new movement patterns that require preserving balance are essential. For example, patients with missing ankle and knee joints may need to adopt adjustment strategies to regain stability during locomotion.

Multi-factorial components contribute to postural balance and there might be other contributing factors have not been found. Although balance control strategies in LEA are different from the general population, the contributing elements are similar. Horak [3] suggested that six sub-components are required to retain postural balance, including biomechanical constraints, movement strategies, sensory strategies, orientation in space, control of dynamics, and cognitive processing. The studies of sensory strategies for balance control demonstrated the important role of integrations among visual, vestibular, and proprioception

* Corresponding author. Tel.: +60 3 79676808; fax: +60 3 79674579.
E-mail addresses: kupeixuan@gmail.com (P.X. Ku), azuan@um.edu.my (N.A. Abu Osman), drirwan1@gmail.com (W.A.B. Wan Abas).
[1] Tel.: +60 3 79675201; fax: +60 3 79674579.
[2] Tel.: +60 3 79674581; fax: +60 3 79674579.

0966-6362
http://dx.doi.org/10.1016/j.gaitpost.2013.07.006

elements in quiet standing. Acquisition of motor control through the central nervous system stimulates the reflective output of movement, where the incoming information obtained from the sensory systems is transmitted to the nervous system. Moreover, the presence of ankle strategy that assists in balance recovery generates compensatory torque around the ankle joints during small motions, whereas hip strategy helps in sustaining balance around the hip joints during larger movement.

Static balance control serves as a balance indicator of dynamic control via postural sway. Postural sway can be defined as the deviation in the position of the centre of pressure (CoP) on the supporting surface. As the upright standing posture is a complicated task for amputees, three main aspects are used to measure the human standing posture: (1) body segment displacement, (2) muscle activity, and (3) movement pattern of CoM and CoP [4]. The most frequently measured parameter is CoP sway. Among different methods for assessing CoP, the force plate, which involves measurement of CoP displacement with transducers during standing posture, is commonly used.

Horak [3] reviewed the interaction and contribution among various physiological systems associated with balance. However, earlier findings were only limited for the general population. The present systematic review provides summaries of literature studies on standing balance characteristic in LEA. Furthermore, the review investigates the association between these balance characteristics and balance ability among LEA patients.

2. Methods

2.1. Search strategy

The electronic search of databases performed in May 2013 was limited to PubMed, Web of Science, Medline, Scopus, and CINAHL. The articles were limited from January 1975 to May 2013 (including E-pub ahead of print publication). The key MESH terms included "balance", "amputee", and "standing". A comprehensive search was performed with the combination of the other relevant keyword search terms: "static", "lower limb", "stance", and "control". Additional manual search was supplemented by manual screening conducted for relevant articles based on reference lists of the retrieved articles. The additional search was performed to avoid the possibility of those overlooked articles.

2.2. Eligibility

Only full-text articles in English were selected from the electronic databases. The search strategy was independently performed by two authors (KPX and NAAO). If article disagreement in screening process existed, the article was discussed to reach consensus. The titles and abstracts screening process included articles on studies that focused on the investigation of amputees' balance for static standing posture. Articles that met the following criteria were considered: (1) human participant, (2) focus on amputees, (3) studies on variables of static balance, and (4) peer-reviewed, full scientific-based articles. Articles that focused on static balance's modelling, gait analysis, intervention in gait rehabilitation, and effect of prosthetic design were excluded, as well as published reports in conference proceedings. No restriction was applied regarding the sex, age, and year since amputation of the participants.

2.3. Review process

Duplicate articles from different databases were removed. The title and abstract for the selected articles were first screened according to the eligibility criteria. Further full-text evaluation was performed if the title and abstract could not provide adequate information for the article screening process. Rejected articles were re-screened to avoid misinterpretation.

2.4. Assessment of methodological quality

A standardized methodological quality assessment tool does not exist in the field that investigates the risk factor of human balance. Systematic methodological quality assessment method was used to evaluate the quality of retrieved articles and minimize reviewer's bias. Peters et al. [5] utilized 20 appraisal questions as quality indicator to assess 20 reviewed articles. The appraisal questions that they developed was around the major research aims such as objective, study design, subjects' characteristic, sample size, equipment design, movement task, statistical analysis method, key findings, limitation and conclusion.

The evaluation in current review was based on the modification of previous established appraisal criteria [5]. The reviewers specifically assessed the retrieved articles with appraisal questions that were modified based on the main aims of this review, which related to biomechanical evaluation in static balance (see Table 1). The overall score provided a measure in standardized quality indicator and enabled the comparison of research quality among articles. Other considerations were addressed for the full understanding of items that were not described clearly.

3. Results

3.1. Literature search yield

Initially, the electronic database screening process yielded 135 articles. The title and abstract screening process eliminated 91 articles, and agreement was reached for 44 articles, which were identified to be related with the aim of the literature study. Following the eligibility criterion of full-text, 18 articles were selected for review. Five articles were retrieved from the reference lists, yielding a total of 23 articles for the review process (Fig. 1). The most common reason of the articles elimination from analysis was the use of an intervention in gait rehabilitation.

3.2. Quality of reviewed articles

The methodological quality scores for 23 reviewed studies are presented in Table 2. Most of the studies provided complete information on the objective, study design, study interest, main outcomes, and conclusion. A total of 12 articles provided study limitations. The quality assessment scores ranged from 57% to 86% and 16 studies satisfied at least 70% to 90% of the questions [6–21].

Table 1
Methodological quality assessment used in this systematic review.

Question
1. Is the objective of the study clearly described?
2. Is the study design clearly described?
3. Are the subjects' characteristics and details clearly provided?
4. Is the practice trial in the study clearly stated?
5. Is the study randomized to the study group clearly stated?
6. Is this double blind study?
7. Is the distance of foot placement between legs clearly described?
8. Is equipment design and set up clearly described?
9. Are the movement tasks clearly defined?
10. Are appropriate statistical methods used in data analysis clearly defined?
11. Is the actual probability value reported for main outcome clearly stated?
12. Are the main outcomes measure clearly stated?
13. Are the limitations of the study clearly stated?
14. Are the conclusion drawn from the study clearly stated?

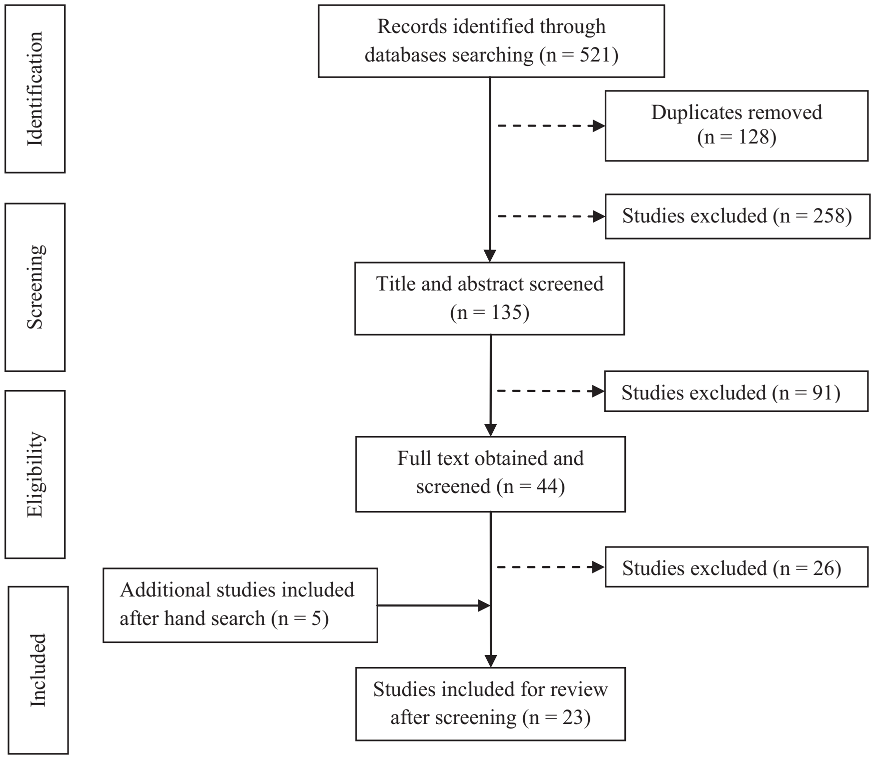

Fig. 1. Flowchart of reviewed studies.

Most of the studies described the statistical test used. However, two studies did not clearly mention their statistical analysis method [22,23].

3.3. Participants

Various physical characteristics of the participants in the reviewed articles are shown in Table 3. Ten articles provide insufficient data on the physical characteristics of tested participants [9,11–13,15,20,24,25,27,28]. Only few articles provided other characteristics, such as side of amputated limb [8,11,12,14,16,19,25,27] and type of prostheses used [8,10,16,17,19,21–23,26,27]. The number of participants varied throughout the reviewed articles, with greater number being 213 persons and two articles testing below 10 persons. The participants were categorized into children, young adults, middle-aged adults, and older adults, where all could stand independently. Two articles involved school-aged children (aged 6–12) [6,22], two articles

Table 2
Rating score for the assessment of methodological quality from reviewed articles.

Study	Question														Total score	Overall percentage
	1	2	3	4	5	6	7	8	9	10	11	12	13	14		
Andrysek et al. [6]	2	2	2	2	N	2	N	2	2	1	2	0	0	2	19/24	79.17
Barnett et al. [8]	2	2	2	0	0	2	0	2	1	2	2	2	1	2	20/28	71.43
Curtze et al. [10]	2	2	1	0	0	2	1	2	1	2	2	2	2	1	20/28	71.43
Nederhand et al. [16]	2	2	2	0	2	2	2	2	2	2	2	2	1	0	23/28	82.14
Gaunaurd et al. [12]	2	2	2	0	N	1	0	2	2	1	2	2	2	2	20/28	71.43
Hlavackova et al. [24]	2	2	1	0	0	2	0	2	2	1	2	2	1	0	17/26	65.38
Mayer et al. [14]	2	2	2	2	0	N	1	2	2	2	2	2	2	2	22/26	84.62
Lenka and Tiberwala [23]	2	2	1	0	0	1	2	2	2	0	0	2	0	2	16/28	57.14
Duclos et al. [11]	2	2	1	1	1	2	2	2	2	2	2	2	0	2	23/28	82.14
Rougier and Bergeau [18]	2	2	2	0	2	2	2	2	2	2	2	1	0	2	23/28	82.14
Vanicek et al. [19]	2	2	2	0	0	2	0	2	2	2	2	2	2	2	22/28	78.57
Vrieling et al. [21]	2	2	2	2	0	2	0	2	2	2	2	2	2	0	22/28	78.57
Duclos et al. [25]	2	2	1	0	0	2	2	0	2	2	2	2	1	1	19/28	67.86
Quai et al. [17]	2	2	1	0	2	2	2	2	2	2	1	2	2	2	24/28	85.72
Buckley et al. [9]	2	1	2	2	1	1	2	2	2	2	2	2	1	2	24/28	85.72
Nadollek et al. [26]	2	2	1	0	1	2	0	2	1	2	2	2	0	2	19/28	67.86
Viton et al. [20]	2	2	2	0	2	2	2	2	2	1	2	2	0	2	23/28	82.14
Mouchnino et al. [15]	2	2	1	2	0	2	2	2	2	2	2	2	0	2	23/28	82.14
Aruin et al. [7]	2	2	2	2	0	2	2	1	2	1	0	2	0	2	20/28	71.43
Hermodsson et al. [13]	2	2	2	0	0	2	1	2	1	2	2	1	1	2	20/28	71.43
Vittas et al. [27]	2	1	1	0	0	2	2	1	2	2	2	1	0	2	18/28	64.29
Clark and Zernicke [22]	2	2	2	0	0	2	2	1	2	0	2	2	0	2	19/28	67.86
Fernie and Holliday [28]	2	2	1	0	0	2	0	2	2	1	2	2	0	2	18/28	64.29

Evaluated as: 2 = Yes, 1 = Limited detail, 0 = no, N = Not applicable.

Table 3
Participants' demographic characteristic.

Study	Aetiology	Level	No. of participant	Gender		Age (years)	Height (cm)	Weight (kg)	Years since amputation
				Male	Female				
Andrysek et al. [6]	Vascular/cancer	TFA	3	1	2	12.7 ± 4.7	152.3 ± 18.7	48.7 ± 21.5	1.4 ± 0.6
	Vascular/cancer	VN	3	1	2	11.0 ± 2.6	149.0 ± 14.9	44.7 ± 17.7	1.7 ± 1.0
		Control	10	5	5	10.7 ± 2.8	147.0 ± 18.7	44.0 ± 13.2	N
Barnett et al. [8]	Vascular/ non-vascular	TTA	7	7	0	56.1 ±14.9	182 ± 8	91.7 ± 11.4	-
Curtze et al. [10]	Trauma/vascular/ other	TTA	15	–	–	55.1 ± 9.8	183 ± 52	92.5 ± 13.9	7
		Control	13	–	–	53.1 ± 10.6	187 ± 56	87.2 ± 10.1	N
Nederhand et al. [16]	Trauma/vascular/ other	TFA	6	5	1	52.3 ± 6.6	174.3 ± 7.5	76.8 ± 11.9	10.3 ± 3.9
	Trauma/vascular/ other	TTA	8	7	1	49.1 ± 14.8	184.0 ± 7.1	88.4 ± 15.8	11.8 ± 10.0
Gaunaurd et al. [12]	Trauma/vascular/ other	TFA	44	37	10	52.6 ± 13.7	–	–	12.6 ± 14.5
	Trauma/vascular/ other	KD	3						
Hlavackova et al. [24]	Trauma	TFA	8	–	–	26.1 ± 13.5	–	–	5.8 ± 2.5
Mayer et al. [14]	Vascular	TTA-SPU	10	8	2	61.1 ± 10.5	172 ± 9	82.9 ± 17.9	4.15 ± 2.4
	Vascular	TTA-FFA	18	12	6	64.8 ± 9.5	164 ± 10	65.8 ± 16.0	0.47
Lenka and Tiberwala [23]	–	TTA-SS	20	–	–	30.7 ± 1.2	163 ± 14.8	65.9 ± 3.9	–
	–	TTA-MS				36.0 ± 11.5	159 ± 3.6	60.7 ± 10.8	
Duclos et al. [11]	Trauma/cancer	TFA	4	–	–	51.3 ± 7.8	–	–	8.3 ± 8.6
	Trauma/cancer	TTA	10	–	–	39.5 ± 9.7	–	–	4.2 ± 3.9
	Trauma/cancer	KD	1	–	–	36	–	–	4.5
		Control	17	–	–	38 ± 10	–	–	N
Rougier and Bergeau [18]	Trauma	TFA	11	9	2	49.6 ± 16.8	170 ± 9.0	75.9 ± 17.1	–
	Trauma	TTA	15	13	2	41.7 ± 11.3	175 ± 7.5	74.0 ± 14.3	
Vanicek et al. [19]	–	TTA	9	7	2	58.6 ± 12.3	171 ± 14.1	76.0 ± 15.9	8.1 ± 9.7
		Control	9	5	4	61.1 ± 15.9	173 ±14.0	79.6 ± 12.8	N
Vrieling et al. [21]	Trauma/vascular/ cancer	TFA	3	6	2	51.8 ± 12.7	178 ± 9	83.3 ± 9.7	21.5
	Trauma/vascular/ cancer	TTA	5						
		Control	9	8	1	44.8 ± 9.9	184 ± 7	85.6 ± 9.1	N
Duclos et al. [25]	Trauma/cancer	TFA	1	–	–	51.3 ± 7.8	–	–	8.3 ± 8.6
	Trauma/cancer	TTA	9	–	–	40.7 ± 9.5	–	–	3.9 ± 2.4
	Trauma/cancer	KD	4	–	–	36	–	–	4.5
		Control	18	–	–	37 ± 10	–	–	N
Quai et al. [17]	Vascular	TTA	22	16	6	71.7 ± 9.62	170 ± 7	80.9 ± 21.9	2.98 ±1.72
Buckley et al. [9]	Trauma	TFA	3	3	0	25.7 ± 5.8	–	–	–
	Trauma	TTA	3	3	0				
		Control	6	6	0	24.7 ± 2.7	–	–	N
Nadollek et al. [26]	Vascular	TTA	20	–	–	71.7 ± 9.6	170 ± 7	80.9 ± 22.0	2.98
Viton et al. [20]	Trauma	TTA	5	5	0	34.8	–	–	–
		Control	5	5	0	Aged-matched	–	–	N
Mouchnino et al. [15]	Trauma	TTA	5	5	0	Range from 24 to 59			–
		Control	5	5	0		–	–	N
Aruin et al. [7]	Vascular	TTA	6	5	1	53.3 ± 8.1	176 ± 2	80.4 ± 3.1	21.5 ±10.4
		Control	6	5	1	54.5 ± 10.5	172 ± 4	77.8 ± 3.7	N
Hermodsson et al. [13]	Trauma	TTA	36	15	3	63.9 ± 10.0	–	–	Men: 36.3 ± 19.4 Women:11.3 ± 11.0
	Vascular	TTA		12	6	68.8 ± 12.0	–	–	Men: 7.0 ± 5.7 Women:5.0 ± 4.7
		Control	27	19	8	69.6 ± 9.8	–	–	N
Vittas et al. [27]	Trauma/vascular	TTA	20	18	2	61	–	–	–
		Control	–	–	–	–	–	–	–
Clark and Zernicke [22]	Trauma/vascular	TFA	2	1	4	11.3 ± 2.1	139.2 ± 6.2	36.6 ± 11.9	> 4
	Trauma/vascular	KD	3						
Fernie and Holliday [28]	–	TFA	50	–	–	53	–	–	–
	–	TTA	29	–	–	58	–	–	–
		Control	134	–	–	50	–	–	–

FFA: first-fitted amputees; KD: knee disarticulation; MD: medium Stump; N: not applicable; SPU: skilled user; SS: short stump; TFA: transfemoral amputee; TTA: transtibial amputee; VN: Van Ness.

assessed young adults (aged 19–29) [9,24], ten articles assessed middle-aged adults (aged 30–59) [7,8,10,12,16,18,20,21,23,28], and five articles involved older adults (aged 60 and above) [13,14,17,26,27]. Four other studies had mixed age group of LEA patients [11,15,19,25]. The participants were categorized into transfemoral amputees, transtibial amputees, van ness amputees, knee disarticulation amputees, and healthy controls (Table 3). One of the articles utilized data-normalizing technique for statistical analysis [19].

3.4. Study procedure

All the articles implied a specific measurement protocol for studies of balance (Table 4). Eleven articles assessed the balance

Table 4
Data extraction from reviewed articles.

Study	Conditions	Protocol	Instrumentation	Sampling rate (Hz)	Outcomes measures	Findings
Andrysek et al. [6]	BPS, BD, EO	Intervention for 4 weeks with 20 min each session. Stand still with footwear and hand placed alongside. The feet placed align their heels. 3 trials performed and 1 min for each trial.	Vicon MX^{C} system, Wii Fit	1200	CoP excursion	TFA > VN > control
					CB&M score	TFA < VN < control
Barnett et al. [8]	BPS, BD, EO	Intervention for 3 sessions. Stand still with flat footwear. Duration 8 s. Limit of stability test movement. Fall effect	NeuroCom Equitest®	100	SOT	Changes occur in utilizing somatosensory and visual inputs
					LOS	Increased in endpoint CoG excursion and directional control
Curtze et al. [10]	BPS, BD, EO	Stand still with feet parallel. The feel set to 20% the height about the hip width. 3 trials performed. Fall effect	Vicon system and force platform	1000	Ankle joint moment	TTA: NA leg > A leg Control: = between 2 legs
					Hip joint moment	TTA: NA leg = A leg Control: = between 2 legs
Nederhand et al. [16]	BPS, BD, EO	Stand still with hands placed alongside. Feet placed 20 cm apart. 3 trials performed and 90 s for each trial. 1–2 min for resting. Dynamic movement.	Computer-controlled dynamic motion platform	360	Load distribution	NA leg > A leg
Gaunaurd et al. [12]	BPS, BS, EO	Stand comfortably with base of support of 10 cm	Laser-Line™	N	Limb length	NA leg > A leg
					PII	NA leg < A leg
					Hip extension	NA leg > A leg
Hlavackova et al. [24]	BPS, BS, EC	Stand still with hands placed alongside. Feet separated 10 cm. 3 trials performed and 30 s for each trial. Resting for 1 min	Zebris FDM-S Multifunction Force Measuring Plate system	100	Load distribution	NA leg > A leg
					CoP amplitude	NA leg > A leg
					CoP velocity	NA leg > A leg
					Regularity of CoP	NA leg < A leg
Mayer et al. [14]	BPS, BS, EO	Stand still with feel parallel at hip width. 2 trials performed and 20 s for each trial. 2–3 min for resting. Concentrate on target located 2 m away	Force plate	100	Load distribution	FFA > SPU
					CoP excursion	FFA > SPU
Lenka and Tiberwala [23]	BPS, BS, EO/EC	Stand still with footwear and hands placed alongside. Toe angle is 30°. Feet apart for 6 cm. Duration for 2 min. Resting for 1 min	Two load cell based unidirectional force platform	260	CoP excursion	CoP in EC > CoP in EO
					Stump length	Sway area in SS > MS
					RMS	SS = MS
Duclos et al. [11]	BPS, BS, EO/EC	Stand still with feet 3 cm apart from heels. 2 trials performed and 1 min for each trial. Resting for 2 min	NeuroCoM Balance Master®	100	Load distribution	Amp > control in EO & EC; Asymmetry load in EO < EC

					CoP excursion	TTA: NA leg > A leg; Control: slightly < in dominant leg (in both EO and EC)
					CoP velocity	Amp > control in both EO and EC
Rougier and Bergeau [18]	BPS, BS, EC	Stand still with barefoot and hands placed alongside. Toe angle is 30°. Feet separated 9 cm apart. 5 trials performed and 32 s for each trial. Resting for 32 s	Equi+ force platform	64	Load distribution	Asymmetry: TFA > TTA
					CoP excursion	AP and ML shifted in TFA > TTA TTA: CoP shifted forward in NA leg
					CoP amplitude	NA leg > A leg in AP and ML for TFA and TTA
					RMS	CoP: AP = ML
Vanicek et al. [19]	BPS, BS, BD, EO	Stand still with hands placed alongside. 3 trials performed and 20 s for each trial	NeuroCom Equitest®	100	SOT	Faller = Nonfaller
					MCT	Faller = Nonfaller
Vrieling et al. [21]	BPS, BD, EO/EC	Hands placed alongside. Feet position was self-selected. Duration for 60 s. 1 min for resting. The platform movements were moved sinusoidally at 1 Hz	Computer assisted rehabilitation environment	100	Load distribution	Asymmetry: Amp > control
					GRFy	NA leg: Amp > control in EO & EC A leg: Amp > control in EO
					CoPy excursion	NA leg: Amp > control in EO A leg: Amp < control in EC
Duclos et al. [25]	BPS, BS, EC	Stand still with feet separated 3 cm apart from heels. Duration for 1 min. 5 min for resting. 2 pre-vibration and 7 post-vibration tests	NeuroCom Equitest®	100	CoP excursion	TTA: NA leg > A leg Control: slightly < in right leg
					CoP velocity	Amp > control
					CoP excursion in muscle vibration effect	Trapezius vibration: Sway in amp > control Gluteus medius vibration: Sway in amp = control
Quai et al. [17]	BPS. BS, BD, EO/EC	Stand still with heel separate 17 cm apart and toe angle is 14°. Duration for 40 s	Kistler force plate	100	CoP excursion	EO: NA > A leg in AP and ML EC: NA > A leg in AP and ML
					CoP excursion in Vibration sense	EO&EC: AP > ML in NA leg
					CoP excursion in pulse score	Lower scorer have greater CoP in ML
Buckley et al. [9]	BPS, BS, BD, EO/EC	Intervention for 3 times per week with 30 min per session. Comfortable standing with hands placed on hips. Feet placed greater than 15 cm. 3 trials performed and 30 s for each trial	Kistler force plate, modified dynamic stabilimeter	100	CoP excursion	AP > ML AP and ML: Amp > control

Table 4 (*Continued*)

Study	Conditions	Protocol	Instrumentation	Sampling rate (Hz)	Outcomes measures	Findings
					BD	Amp < control in both AP and ML Balance in EO > EC
Nadollek et al. [26]	BPS, BS, EO/EC	Stand still with feet placed separately for 17 cm between heels. Toe angle is 14°. Duration for 40 s	Kistler force plate, dynamometer, B&L stride analyzer	100	Load distribution	NA leg > A leg Performance in EO = EC
					CoP excursion	NA leg > A leg in EO and EC AP: EO < EC, ML: EO = EC
Viton et al. [20]	UPS, BD, EO	Stand still with feet placed 10 cm apart for 20 trials. Laterally raised one leg as fast as possible to 45°	Kistler force plate	100	CoG position	AP: Amp > control ML: Amp = control
					RMS	Control > Amp
Mouchnino et al. [15]	BPS, BS, EO	Stand still with hands placed behind the back. Feet placed 8 cm and toe angle is 60 ° for 20 trials. The eyes gazed ahead horizontally	Kistler force plate	‘100	CoG position	AP: Amp > control ML: Amp = control
					RMS	Control > Amp
Aruin et al. [7]	BPS, BD, EO	Stand still with hands placed alongside. Feet placed 30 cm apart. 6 trials performed and 10 s for each trial. Resting period is 2 min	AMTI biomechanical platform	–	Anticipatory changes in muscle activity	NA leg > A leg
Hermodsson et al. [13]	BPS, UPS, BS,BD, EO/EC	Stand still with hands placed alongside. 3 trials performed and 30 s for each trial	Kistler force plate	50	CoP excursion	AP: TTA (trauma) < TTA (vascular) & control ML in feet close/EC: TTA Vascular > control
Vittas et al. [27]	BPS, BS, EC	Stand still with hands placed alongside. Medial side of feet separated by 1 cm. Duration for 30 s	Force plate	–	CoP excursion	Amp (below aged 59) < Control (above aged 59) in both AP and ML
Clark and Zernicke [22]	BPS, BS, BD, EO	Stand still with hands placed alongside. Duration for 10 s	Kistler force plate	–	CoP excursion	NA leg > A leg Sway in AP > ML
Fernie and Holliday [28]	BPS, BS, EO/EC	Stand still. Duration for 3 min. 3 min for resting period	Potentiometric displacement transducer	–	CoP velocity	TTA > TFA > control in EC TTA> TFA and control in EO Increase with age

A leg: amputated leg; Amp: amputee; AP: anterior-posterior direction; BD: balance in dynamic standing; BPS: Bipedal Standing; BS: balance in static standing; EC: eyes closed; EO: eyes open; FFA: first-fitted amputee; MCT: motor control test; ML: medial-lateral direction; MS: medium stump; NA leg: non-amputated leg; LOS: Limits of Stability Test; RMS: root mean square; SOT: Sensory Organization Test; SPU: skilled user; SS: short stump; TFA: transfemoral amputee; TTA: transtibial amputee; UPS: unipedal standing; VN: Van Ness amputee.

Table 5
Summary of the CoP-related parameters measured on standing posture.

Study	Groups	Visual condition	Parameter	Amputee	Control	*p* Value
Andrysek et al. [6]	TFA, VN, control	EO	RMS (AP)	8.1 ± 3.7 mm	5.1 ± 2.0 mm	–
			RMS (ML)	10.3 ± 5.3 mm	5.7 ± 1.2 mm	–
			V_{CoP} (AP)	776.0 ± 359.5 mm/s	494.5 ± 190.5 mm/s	–
			V_{CoP} (ML)	588.5 ± 328.2 mm/s	241.0 ± 90 mm/s	–
			Sway Area	1493 ± 1420 mm^2	364 ± 200 mm^2	–
Hlavackova et al. [24][a]	TFA	EC	A_{CoP}	NA: ~8.2 mm	–	<0.001
				A: ~3.5 mm	–	
			V_{CoP}	NA: ~35 mm/s	–	<0.01
				A: ~15 mm/s	–	
			Reg_{CoP}	NA: ~ 0.7	–	<0.05
				A: ~0.9	–	
Mayer et al. [14]	TTA	EO	D_{CoP} (AP)	SPU: 331.1 ± 151.4 mm	–	0.145
				FFA: 398.9 ± 141.1 mm	–	
			D_{CoP} (ML)	SPU: 255.9 ± 139.6 mm	–	0.040
				FFA: 378.7 ± 154.5 mm	–	
			V_{CoP}	SPU: 23.4 ± 8.3 mm/s	–	0.071
				FFA: 33.1 ± 13.4 mm/s	–	
Lenka and Tiberwala [23]	TTA	EO	RMS (AP)	SS: 1.66 ± 1.04 mm	–	<0.05
				MS: 1.70 ± 0.5 mm	–	
			RMS (ML)	SS: 2.02 ±1.02 mm	–	0.297
				MS: 1.74 ± 0.5 mm	–	
			V_{CoP} (AP)	SS: 1.34 ± 0.17 mm/s	–	0.006
				MS: 1.21 ± 0.18 mm/s	–	
			V_{CoP} (ML)	SS: 2.63 ± 0.33 mm/s	–	0.224
				MS: 2.42 ± 0.31 mm/s	–	
			Sway Area	SS: 93.84 ± 17.47 mm^2	–	<0.001
				MS: 50.6 ± 22.60 mm^2	–	
Duclos et al. [11]	TFA,TTA, KD, control	EO	D_{CoP}	7 ± 2 mm	2 ± 1 mm	0.034
			V_{CoP}[a]	~3.0 mm/s	~4.0 mm/s	0.157
		EC	D_{CoP}	11 ± 3 mm	2 ± 1 mm	0.003
			V_{CoP}[a]	~3.0 mm/s	~3.5 mm/s	0.043
Vrieling et al. [21][b]	TFA, TTA, control	EO	RMS	NA: 3.38 ± 1.69 mm	1.91 ± 0.62 mm	0.027
				A: 1.36 ± 0.41 mm		0.053
		EC	RMS	NA: 4.28 ± 2.18 mm	2.82 ± 0.87 mm	0.082
				A: 1.39 ± 0.41 mm		0.001
Duclos et al. [25]	TFA, TTA, KD, control	EC	D_{CoP}	12.5 ± 4.0 mm	1 ± 2 mm	<0.05
			V_{CoP}	15.0 ± 2 mm/s	10.0 ± 1 mm/s	<0.05
Quai et al. [17]	TTA	EO	D_{CoP} (AP)	NA: 84.0 ± 41.6 mm	–	–
				A: 43.4 ± 23.8 mm	–	
			D_{CoP} (ML)	NA: 15.2 ± 11.7 mm	–	–
				A: 15.1 ± 7.7 mm	–	
		EC	D_{CoP} (AP)	NA: 119.0 ± 49.8 mm	–	–
				A: 52.8 ± 20.5 mm	–	
			D_{CoP} (ML)	NA: 20.2 ± 13.8 mm	–	–
				A: 19.2 ± 9.9 mm	–	
Buckley et al. [9][a]	TFA, TTA, control	–	D_{CoP}	AP: ~2 mm	AP: ~5 mm	<0.05
				ML: ~15 mm	ML: ~10 mm	<0.05
Nadollek et al. [26]	TTA	EO	RMS (AP)	NA: 8.40 ± 4.16 mm	–	<0.05
				A: 4.34 ± 2.39 mm	–	
			RMS (ML)	NA: 1.53 ± 1.16 mm	–	0.941
				A: 1.51 ± 0.77 mm	–	
		EC	RMS (AP)	NA: 11.85 ± 4.98 mm	–	<0.05
				A: 5.28 ± 2.05 mm	–	
			RMS (ML)	NA: 2.02 ± 1.38 mm	–	0.728
				A: 1.92 ± 0.99 mm	–	

Table 5 (*Continued*)

Study	Groups	Visual condition	Parameter	Amputee	Control	*p* Value
Viton et al. [20]	TTA, control	EO	D_{CoG}	AP: 12.8 ± 2.7 mm ML: 6.97 ± 1.04 mm	– ML: 2.4 ± 0.76 mm	– –
			RMS	4.69 ± 2.55 mm	5.54 ± 2.78 mm	<0.02
Mouchnino et al. [15]	TTA, control	EO	D_{CoG}	AP: 12.8 ± 2.7 mm ML: 6.97 ± 1.04 mm	– ML: 2.4 ± 0.76 mm	– –
			RMS	4.69 ± 2.55 mm	5.54 ± 2.78 mm	<0.02
Clark and Zernicke [22]	TFA, KD	EO	D_{CoP} RMS (AP) RMS (ML)	37 ± 14 mm 6.1 ± 3.2 mm 3.5 ± 0.6 mm	– – –	– – –
Fernie and Holliday [28]	TFA, TTA, control	EO	V_{CoP}	TFA: 0.91 mm/s TTA: 1.17 mm/s	0.97 mm/s	>0.05 <0.05
		EC	V_{CoP}	TFA: 1.80 mm/s TTA: 2.14 mm/s	1.39 mm/s	<0.05 <0.05

A leg: amputated leg; A_{CoP}: amplitude of CoP; AP: anterior-posterior direction; CoG: centre of gravity; CoP: centre of pressure; EC: eyes closed; EO: eyes open; FFA: first-fitted amputee; KD: knee disarticulation amputee; D_{CoG}: mean of CoG displacement; D_{CoP}: mean of CoP displacement; ML: medial-lateral direction; MS: medium stump; NA leg: non-amputated leg; RegCoP: regularity of CoP; RMS: root mean square; SPU: skilled user; SS: short stump; TFA: transfemoral amputee; TTA: transtibial amputee; V_{CoP}: mean velocity; VN: Van Ness amputee.

[a] Data extracted from bar chart.

[b] The presented results were performed at dynamic platform during dynamic standing.

ability in static standing posture [11,12,14,15,18,23–28], seven articles examined the ability of balance in dynamic standing posture [6–8,10,16,20,21], and five articles examined the ability of balance in static and dynamic standing posture [9,13,17,19,22]. The placement distance between patients' feet ranged from 1 cm [27] to 30 cm [7], and only one study assessed the innominate inclination measurement in balance control [12]. Most of the studies utilized two to three repetition trials in recording the balance performance; nine articles did not clearly report the number of trials used [8,12,17,21–23,26–28].

A force plate was mostly used to assess the pattern of balance variable and thereby evaluate balance performance. Beside from using the single force plate, balance also can be evaluated by the integration of force plate with other systems [7,9,13,15,17,20, 22,26,27], which including Vicon System [6,10], Zebris FDM-S Forceplate System [24], NeuroCoM System [8,11,19,25], and Computer-Assisted Rehabilitation Environment System [21]. In some studies, balance skills were evaluated using functional assessment, such as Berg Balance Scale [11,25], Sensory Organization Test [8], Community Balance and Mobility Scale [6], Activities-Specific Balance Confidence scale [21], Amputee Activity Score [21], Functional Reach Test [17], and Visual Analogue Scale [26].

3.5. Variability in measured parameters

The CoP-related outcomes measured were CoP excursion, CoP velocity, CoP amplitude, and root mean square of CoP (Table 5). The majority of studies used these CoP-related outcomes [6,9,11,13,14,17,18,21–28]. These studies investigated the association between CoP displacement and other subscales: load distribution, level of amputation, duration of wearing prostheses, sensory perception, and sway direction. Only two articles evaluated ankle and hip moment [10,12] and two articles examined stump length [12,23] as a variable in their studies. With the CoP-related variables, the changes of CoP in balance performance was examined and served as evidence for the association with other subscales.

Overall, the evidence indicates that LEA patients exhibit greater postural imbalance compared with healthy controls. The mean CoP position of LEA patients generally veered towards the non-amputated side (1.1 ± 0.3 cm), whereas the healthy controls was only slightly towards the dominant side (0.2 ± 0.1 cm). Higher CoP velocities were found in LEA patients than in healthy controls [11,25,28]. Additionally, the non-amputated side also showed greater amplitudes of CoP along the anterior-posterior (AP) and medial-lateral (ML) directions [18,24].

3.6. Load distribution

Seven articles investigated body load distribution (Table 4). Among these articles, four studies showed that the weight distribution of non-amputated leg was larger compared with the amputated leg [11,16,24,26]. Load distribution was generally asymmetrical among LEA patients. The load distribution asymmetry for first-fitted users was greater than skilled prosthetic users [14], whereas the healthy controls had equal distribution between both legs. In Curtze et al. [10], 69% of transtibial amputee's body weight was distributed more under the ankle of NA leg, whereas healthy controls had equally distributed load under the ankle joints (left: 42%; right: 36%) and hip joints (left: 12%; right: 11%).

3.7. Sensory perception

Sensory perception can be categorized into visual and somatosensory inputs. Overall, ten articles that examined balance for LEA patients included sensory perception as a variable for their studies. Eight articles investigated CoP changes under different visual conditions (open/closed eyes) [9,11,13,17,19,21,23,26,28]. Most of these studies reported that the absence of visual input increases the postural sway among LEA patients [9,11,23,26]. Nadollek et al. [26] highlighted that an increase in AP sway displacement occurs under the NA leg for the closed eyes condition compared with the open eyes condition, whereas no ML sway difference between both legs was observed under both conditions. The effect of somatosensory input [8,17,19] and muscle vibration [7,25] towards changes in balance stability was also studied. Only a few studies investigated on these subscales. Balance performance is significantly increased with the aid of visual and somatosensory inputs [8].

3.8. Other variability

Overall, two studies examined the association between stump length and balance ability. The sway area for individuals with short stump was larger than individuals with medium stump [23]. In the studies of Gaunaurd et al. [12], limb length discrepancy was found in 66% of participants. These works showed the effect of limb length on the balance stability of LEA patients.

4. Discussion

The aim of this review was to summarize and update readers on the current published research explicitly related to balance variables in LEA. Given the intricate interaction among balance domains, the understanding in measured balance variables is crucial for improving postural control and helps in rehabilitation. This review examined 23 studies involving LEA in different age groups under static and dynamic stance in the past 38 years.

As the reviewed studies applied different methodological protocols, meta-analysis was not feasible due to the lack of data homogeneity. Methodological challenge particularly increased with the interpretation of balance components as standard protocols were affected by many dependent variables: sample size, sample duration, foot distance, and difficulty of task performed. For example, the LEA studies reported that the distance of foot placement varied in a broad range. However, broad stance was demonstrated to facilitate greater postural control in normal quiet standing [29]. Discrepancies in foot distance may influence the reliability of the results in this review. The lack of studies reported on the lifestyle of LEA patients and the time of day for research were common deficiencies in this review. The level of physical activity related to muscle strength and the time of day during experiments should be considered as potential factors, as the impact on postural control showed significance in normal quiet standing [30].

For the inconsistencies of methodological reporting, quality assessment served as the key methodological consideration to ensure that the limitations in the reviewed studies were taken into consideration. None of the reviewed articles scored below the baseline; 50% score was considered as the acceptable mean. All details from the studies were important to avoid uncertainty and bias, as well as improve transparency of the methodological protocol.

The selection of postural control measurement tools did not affect the potential variables. In fact, only few of the studies reported on the ICC value for the measured variables. The test–retest reliability was emphasized in order to validate the reliability statistic. High reliability indicates that the variable is strongly associated with postural sway, whereas low reliability implies a weaker effect on sway.

Findings from this review highlight that changes in postural control is associated with increased postural sway. The evidence clearly described that the transfemoral group exhibits greater postural sway, followed by transtibial and the healthy group. A greater sway is more likely to occur in the AP than the ML direction. This finding supports the speculation that the missing limb leads to changes in balance adjustment process, through more contribution from ankle strategy and muscle strength in sustaining balance. In addition, load distribution asymmetry from the aetiology adaptation process, with postural sway concentrated under the non-amputated leg, may also increase the postural sway. By considering the pattern of load distribution, it may augment the reliability of CoP sway in predicting balance performance.

Visual input is important to compensate the balance impairment due to amputation. Nadollek et al. [26] and Duclos et al. [11] showed an increased CoP sway in the condition with and without vision. In these studies, AP sway fluctuated more under the absence of visual input than with vision. In contrast, Vrieling et al. [21] found no difference, suggesting that visual input does not affect postural control, as CoP sway is similar in both conditions. The magnitude of proprioception input can be affected by visual input and muscle vibration [8,19,25]. Therefore, the sensory system may exhibit a distinct impact on balance, and the compensation mechanism also depends on the change of input information from the sensory system as well as the level of amputation.

In terms of postural control and reason of amputation, limited studies in this review reported their association since the related-details collected in the methodology was insufficient. Given the limited information collected, some possible balance-related factor may still absence in this review. The effect of stump length and type of prosthetic may play a role as balance-related factor, but this aspect was not explored by the reviewed articles. The justification associated with postural sway is often very important. As no test regarding to the confidence level (fear of fall) and sleep quality have been conducted, while these may be the behaviour factors for balance, we suggest that these factors should be tested in future research. The age effect will increase the postural sway for the elderly in the normal population, and this should be considered during experiment. A broad range of age groups throughout the studies limited the analysis of measured variables within particular age groups. The gender effect should also be taken into consideration.

The limitation of this review is that the search strategy only limited to English-based publications. Only five databases were used as search engine for articles, and some articles may have been missed out in the search. Manual search was performed for the missed relevant articles. The inclusion criteria were limited to the task of quiet standing, thereby excluding findings related to standing in articles that directly tested gait analysis and gait balance intervention.

5. Conclusion

This review indicates that LEA patients experienced greater imbalance compared with the normal population in majority of the reviewed studies. This difference is associated with load distribution asymmetry, where more load is applied to the non-amputated leg as a result of aetiology adaptation. However, an argument arises as regards to the impact of visual input on postural control. Insufficient information prevents the analysis of related measured variables. The application of measured variables is recommended to include details such as stump length, prosthetic type, patients' confidence level, sleep quality, age effect, and gender effect. Hence, further research for the aspects mentioned above is required to enhance and provide a better understanding for LEA postural control.

Acknowledgment

This review work was financially supported by the Malaysia UM/MOHE/HIR grant (Project No: D000010-16001).

Conflict of interest

The authors do not have any conflict of interest which could affect the outcomes of this study.

References

[1] Vamos EP, Bottle A, Edmonds ME, Valabhji J, Majeed A, Millett C. Changes in the incidence of lower extremity amputations in individuals with and without diabetes in England between 2004 and 2008. Diabetes Care 2010;33(12): 2592–7.
[2] Van Gils CC, Wheeler LA, Mellstrom M, Brinton EA, Mason S, Wheeler CG. Amputation prevention by vascular surgery and podiatry collaboration in high-risk diabetic and nondiabetic patients, The Operation Desert Foot experience. Diabetes Care 1999;22(5):678–83.
[3] Horak FB. Postural orientation and equilibrium: what do we need to know about neural control of balance to prevent falls? Age Ageing 2006;35(Suppl. 2):ii7–11.
[4] Balasubramaniam R, Wing AM. The dynamics of standing balance. Trends in Cognitive Sciences 2002;6(12):531–6.
[5] Peters A, Galna B, Sangeux M, Morris M, Baker R. Quantification of soft tissue artifact in lower limb human motion analysis: a systematic review. Gait Posture 2010;31(1):1–8.
[6] Andrysek J, Klejman S, Steinnagel B, Torres-Moreno R, Zabjek KF, Salbach NM, et al. Preliminary evaluation of a commercially available videogame system as an adjunct therapeutic intervention for improving balance among children and adolescents with lower limb amputations. Archives of Physical Medicine and Rehabilitation 2012;93(2):358–66.
[7] Aruin AS, Nicholas JJ, Latash ML. Anticipatory postural adjustments during standing in below-the-knee amputees. Clinical Biomechanics (Bristol Avon) 1997;12(1):52–9.
[8] Barnett CT, Vanicek N, Polman RC. Postural responses during volitional and perturbed dynamic balance tasks in new lower limb amputees: a longitudinal study. Gait Posture 2012;37(3):319–25.
[9] Buckley JG, O'Driscoll D, Bennett SJ. Postural sway and active balance performance in highly active lower-limb amputees. American Journal of Physical Medicine & Rehabilitation 2002;81(1):13–20.
[10] Curtze C, Hof AL, Postema K, Otten B. The relative contributions of the prosthetic and sound limb to balance control in unilateral transtibial amputees. Gait Posture 2012;36(2):276–81.
[11] Duclos C, Roll R, Kavounoudias A, Mongeau JP, Roll JP, Forget R. Postural changes after sustained neck muscle contraction in persons with a lower leg amputation. Journal of Electromyography and Kinesiology 2009;19(4):e214–22.
[12] Gaunaurd I, Gailey R, Hafner BJ, Gomez-Marin O, Kirk-Sanchez N. Postural asymmetries in transfemoral amputees. Prosthetics and Orthotics International 2011;35(2):171–80.
[13] Hermodsson Y, Ekdahl C, Persson BM, Roxendal G. Standing balance in trans-tibial amputees following vascular disease or trauma: a comparative study with healthy subjects. Prosthetics and Orthotics International 1994;18(3): 150–8.
[14] Mayer A, Tihanyi J, Bretz K, Csende Z, Bretz E, Horvath M. Adaptation to altered balance conditions in unilateral amputees due to atherosclerosis: a randomized controlled study. BMC Musculoskeletal Disorders 2011; 12:118.
[15] Mouchnino L, Mille ML, Cincera M, Bardot A, Delarque A, Pedotti A, et al. Postural reorganization of weight-shifting in below-knee amputees during leg raising. Experimental Brain Research 1998;121(2):205–14.
[16] Nederhand MJ, Van Asseldonk EH, van der Kooij H, Rietman HS. Dynamic balance control (DBC) in lower leg amputee subjects; contribution of the regulatory activity of the prosthesis side. Clinical Biomechanics (Bristol Avon) 2012;27(1):40–5.
[17] Quai TM, Brauer SG, Nitz JC. Somatosensation: circulation and stance balance in elderly dysvascular transtibial amputees. Clinical Rehabilitation 2005;19(6): 668–76.
[18] Rougier PR, Bergeau J. Biomechanical analysis of postural control of persons with transtibial or transfemoral amputation. American Journal of Physical Medicine & Rehabilitation 2009;88(11):896–903.
[19] Vanicek N, Strike S, McNaughton L, Polman R. Postural responses to dynamic perturbations in amputee fallers versus nonfallers: a comparative study with able-bodied subjects. Archives of Physical Medicine and Rehabilitation 2009;90(6):1018–25.
[20] Viton JM, Mouchnino L, Mille ML, Cincera M, Delarque A, Pedotti A, et al. Equilibrium and movement control strategies in trans-tibial amputees. Prosthetics and Orthotics International 2000;24(2):108–16.
[21] Vrieling AH, van Keeken HG, Schoppen T, Otten E, Hof AL, Halbertsma JP, et al. Balance control on a moving platform in unilateral lower limb amputees. Gait Posture 2008;28(2):222–8.
[22] Clark LA, Zernicke RF. Balance in lower limb child amputees. Prosthetics and Orthotics International 1981;5(1):11–8.
[23] Lenka P, Tiberwala D. Effect of stump length on postural steadiness during quiet stance in unilateral trans-tibial amputee. Al Ameen Journal of Medical Science 2010;30(1):50–7.
[24] Hlavackova P, Franco C, Diot B, Vuillerme N. Contribution of each leg to the control of unperturbed bipedal stance in lower limb amputees: new insights using entropy. PLoS ONE 2011;6(5):e19661.
[25] Duclos C, Roll R, Kavounoudias A, Roll JP, Forget R. Vibration-induced post-effects: a means to improve postural asymmetry in lower leg amputees? Gait Posture 2007;26(4):595–602.
[26] Nadollek H, Brauer S, Isles R. Outcomes after trans-tibial amputation: the relationship between quiet stance ability, strength of hip abductor muscles and gait. Physiotherapy Research International 2002;7(4): 203–14.
[27] Vittas D, Larsen TK, Jansen EC. Body sway in below-knee amputees. Physiotherapy Research International 1986;10(3):139–41.
[28] Fernie GR, Holliday PJ. Postural sway in amputees and normal subjects. Journal of Bone and Joint Surgery American volume 1978;60(7):895–8.
[29] Bonnet CT. Broad stance conditions change postural control and postural sway. Journal of Motor Behavior 2012;44(2):125–31.
[30] Jorgensen MG, Rathleff MS, Laessoe U, Caserotti P, Nielsen OB, Aagaard P. Time-of-day influences postural balance in older adults. Gait Posture 2012;35(4):653–7.