Clinical Rehabilitation 2006; **20:** 999–1016

Physical capacity and walking ability after lower limb amputation: a systematic review

JM van Velzen Heliomare Research and Development, Wijk aan Zee, **CAM van Bennekom** Heliomare Research and Development and Heliomare Rehabilitation Centre, Wijk aan Zee, **W Polomski**, **JR Slootman** Heliomare, Rehabilitation Centre, Wijk aan Zee, **LHV van der Woude** Institute for Fundamental and Clinical Human Movement Sciences, Faculty of Human Movement Sciences, Vrije Universiteit and Rehabilitation Centre Amsterdam, Amsterdam and **H Houdijk** Heliomare Research and Development, Wijk aan Zee and Institute for Fundamental and Clinical Human Movement Sciences, Faculty of Human Movement Sciences, Vrije Universiteit, Amsterdam, The Netherlands

Received 8th December 2005; returned for revisions 5th February 2006; revised manuscript accepted 4th March 2006.

Objective: To review the influence of physical capacity on regaining walking ability and the development of walking ability after lower limb amputation.
Design: A systematic search of literature was performed. The quality of all relevant studies was evaluated according to a checklist for statistical review of general papers.
Subjects: Lower limb amputees.
Main measures: Physical capacity (expressed by aerobic capacity, anaerobic capacity, muscle force, flexibility and balance) and walking ability (expressed by the walking velocity and symmetry).
Results: A total of 48 studies that complied with the inclusion criteria were selected. From these studies there is strong evidence for deterioration of two aspects of physical capacity (muscle strength and balance) and of two aspects of walking ability (walking velocity and symmetry) after lower limb amputation. Strong evidence was found for a relation between balance and walking ability.
Conclusion: Strong evidence was only found for a relation between balance and walking ability. Evidence about a relation between other elements of physical capacity and walking ability was insufficient. Training of physical capacity as well as walking ability during rehabilitation following lower limb amputation should not be discouraged since several parameters have been shown to be reduced after amputation, although their relation to regaining walking ability and to the development of walking ability remains unclear.

Introduction

In the Netherlands, an estimated 3300 lower extremity amputations are performed every year.[1] Parts of the locomotor system are lost with the amputation. Because of that, function is partly lost. The main purpose of the rehabilitation process is to restore function and to regain an acceptable level of functioning and participation. To reach this goal, a prosthesis is used to compensate for the functional losses if possible.[2,3] Because of that, the rehabilitation of patients with an amputation of the lower extremities focuses on standing and walking ability while wearing a prosthesis.[4] In clinical settings it is generally observed that for most people walking ability improves during rehabilitation. However, reliable

Address for correspondence: JM van Velzen, Rehabilitation Centre Heliomare, Research and Development, Relweg 51, 1949 EC Wijk aan Zee, The Netherlands.
e-mail: j.van.velzen@heliomare.nl

10.1177/0269215506070700

information about the development of walking ability and its underlying mechanisms is lacking.

In earlier reviews, different aspects of amputee walking have been investigated.[5–8] From these reviews it became clear that walking ability after lower limb amputation is multidimensionally defined and can be influenced by many different aspects, such as disease characteristics, personal and external factors. Walking ability can also be influenced by physical capacity. Little systematic knowledge is available, however, about the impact of the physical capacity on walking ability. Therefore the current review will focus on the physical capacity of amputees. In this study the following definition of physical capacity is used: physical capacity is the ability to perform activities of daily living and leisure, determined by the capacities of the physiological system and the neuromuscular system (adapted from Moore *et al.*[9]). Physical capacity can be expressed by the following outcome measures: aerobic capacity, anaerobic capacity, muscle force, flexibility and balance and can be influenced through practice and training.[9]

The purpose of this study is to review the literature on the status and development of the physical capacity and walking ability of amputees and to investigate the influence of the physical capacity on regaining walking ability and the development of walking ability. To describe its development, walking ability is defined by gait characteristics, such as walking velocity and symmetry, and functional outcomes related to walking. To organize the results and to limit the scope of this study the International Classification of Functioning, Disability and Health (ICF) model was used (Figure 1).[10] In this model, walking ability could be seen as part of the amputee's functional ability and influences activities. According to the ICF model, functioning is the result of the interaction between body functions and structures on the one hand and activities and participation on the other hand.[10] In addition, functioning is influenced by the disease or disorder itself and by external (environmental) and personal factors. Only the factors and relationships presented in Figure 1 with bold lines are included in this study. The research questions of this study are:

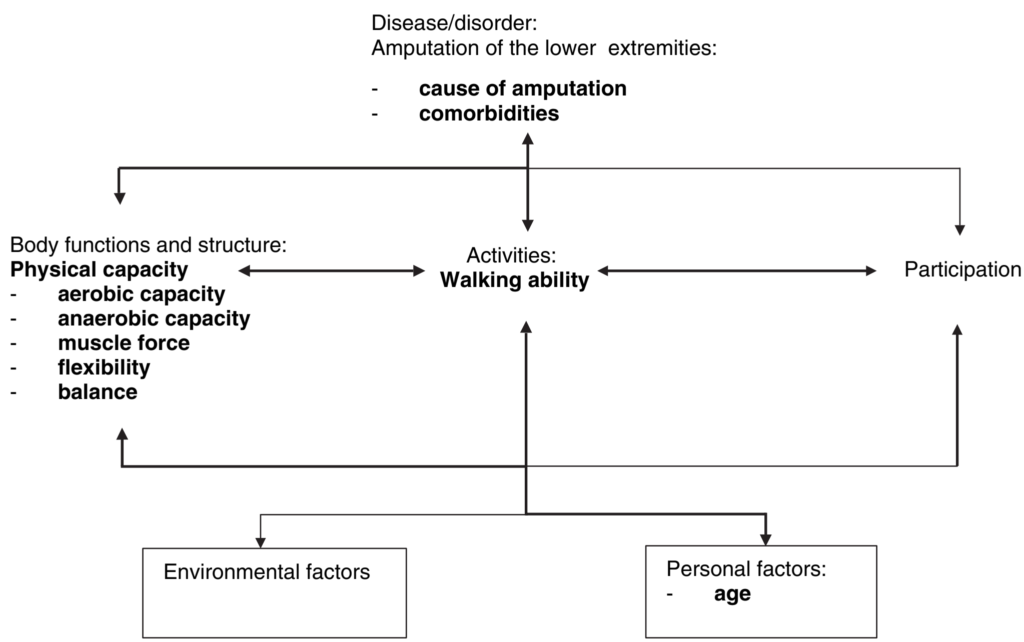

Figure 1 The International Classification of Functioning, Disability and Health (ICF) model adapted to walking ability. Only the bold items and relations will be investigated in this review.

1) What is the status of the physical capacity of amputees and how does this capacity change during rehabilitation?
2) What is the status of the walking ability of amputees and how does walking ability change during rehabilitation?
3) What is the relationship between physical capacity and walking ability?

Methods

A systematic search of the literature was performed in the databases PubMed and Picarta and the Cochrane Library. In Table 1 the keywords and search strategies for all three research questions are given. Studies published before May 2005 and reported in English, Dutch or German were included. References given in relevant reviews were screened for additional literature that was not found by the systematic search of literature.

Table 1 Search strategy

Combinations of search terms	Research question 1	Research question 2	Research question 3
OR	Amput* Prosth*	Amput* Prosth*	Amput* Prosth*
OR	Lower limb Leg	Lower limb Leg	Lower limb Leg
OR	Physic* Balance Postural Strength Force Range of motion Fitness Flexibility Aerob* Anaerob* Efficienc*	Walk* Gait Mobility Ambul*	Physic* Balance Postural Strength Force Range of motion Fitness Flexibility Aerob* Anaerob* Efficienc*
OR	Chang* Alter* Develop*	Ability Perform*	Walk* Gait Mobility Ambul*
OR		Chang* Alter* Develop*	Ability Perform*
Total number of hits	475	158	165

The quality of all relevant studies was evaluated according to a checklist for statistical review of general papers (Table 2) (adapted from Gardner and Altman[11]). For practical reasons, only one author extracted data and assessed methodological quality. A cut-off point was chosen at 60%.[12] All studies that scored at least 6½ points out of 11 were defined as studies with sufficient quality and were taken into account when answering the research questions. The remaining studies were defined as studies with insufficient quality and were not taken into account when answering the research questions because these studies had a high risk of distorted data.

Assessment of evidence from the answering of the research questions was based on both the number of studies and the availability of prospective studies. To be labelled 'strong' at least three studies should be available, of which at least two should be in agreement. Since prospective studies are the most important studies for collecting evidence, the prospective studies counted twice in this analysis and were thus treated as two studies.

Results

Methodological quality

From the search process a total of 48 studies were found (Figure 2). These studies were analysed on methodological quality (Table 3). Thirty-seven studies were defined as having sufficient quality and were included in the remaining review process. Almost all the included studies fulfilled criteria 1 (Was the objective of the study sufficiently described?). However, for most studies it remained unclear whether the instruments of testing were reliable (criterion 4) or no follow-up duration was described (criterion 5). Besides, about half of the studies did not have a study design that was appropriate to achieve the objective (criterion 2), often because the design was not prospective, or did not achieve a satisfactory sample size and response rate (criterion 6). Although three different search strategies were used for the three research questions, the studies found with one strategy were also used to answer the other research questions if possible.

Table 2 Checklist for statistical review of general papers

Criteria	Score[b]
Design features	
1) Was the objective of the study sufficiently described?	Yes–Unclear–No
2) Was an appropriate study design used to achieve the objective?	Yes–Unclear–No
3) Was there a satisfactory statement given of source of subjects?	Yes–Unclear–No
4) Were the instruments of testing reliable?[a]	Yes–Unclear–No
5) Was follow up duration sufficiently described and consistent within the study?[a]	Yes–Unclear–No
Conduct of study	
6) Were a satisfactory sample size and response rate achieved?[a]	Yes–Unclear–No
Analysis and presentation	
7) Was there a statement adequately describing or referencing all statistical procedures used?	Yes–No
8) Were the statistical analyses used appropriate?	Yes–Unclear–No
9) Was the presentation of statistical material satisfactory?	Yes–No
10) Were confidence intervals given for the main results?	Yes–No
11) Was the conclusion drawn from the statistical analysis justified?	Yes–Unclear–No

[a]This question was adjusted to the current review.
[b]Yes = 1 point; unclear = ½ point; no = 0 points.
Adapted from ref. 11.

Walking ability and its underlying mechanisms

The results of this literature study will be described following the stated research questions. The purpose, subjects, design and results of the included studies will not be described in detail here because these are presented in Table 3. In Table 4 the studies used to answer each research question are given and the amount of evidence per question is summarized.

Status and development of physical capacity

As can be seen in Figure 1, physical capacity can be expressed by aerobic capacity, anaerobic capacity, muscle force, flexibility and balance. No studies with sufficient methodological quality were found investigating anaerobic capacity and flexibility.

Concerning aerobic capacity, Chin *et al.*[13] found that the physical fitness of young, traumatic amputees was lower than that of able-bodied subjects. The maximum oxygen uptake ($V\text{O}_2$max) of the amputee group was 18.8 mL/kg per min (SD 4.9) whereas the $V\text{O}_2$max of the able-bodied group was 23.5 mL/kg per min (SD 3.2), a statistically significant difference. The anaerobic threshold of amputees (12.8 mL/kg per min) was also significantly lower than that of able-bodied people (14.3 mL/kg per min). Mean peak workloads of vascular amputees were found to be low during rowing.[14] No statistical significant differences in peak workloads between those using and those not using medication were found in that study, indicating a lower physical fitness for amputees in general.[15] Van Alste *et al.*[16] showed that vascular amputees (mean age 67.4 years) reached a mean maximum heart rate of 124 beats/min during ergometer rowing, which was 80% of the predicted maximum heart rate for healthy subjects ($P < 0.05$). However, half of the subjects were taking medication that could influence heart rate and the endpoint of the test was subjectively chosen by the individual patient. Therefore the heart rate reached may not be the maximum attainable heart rate and the decrease in heart rate after amputation remained doubtful from this study. Endurance training, by performing one-leg cycling,[17] was shown to increase the physical fitness of traumatic amputees to the level of able-bodied subjects.[13] The anaerobic threshold and the maximum oxygen uptake of traumatic amputees both increased significantly after endurance training.[18] From these studies there is insufficient evidence for a deterioration of the aerobic capacity after amputation and for an improvement of aerobic capacity after training (Table 4a).

Several authors investigated the strength of the thigh muscles in transtibial amputees,[19–23] whereas Ryser *et al.*[24] investigated the hip abductor

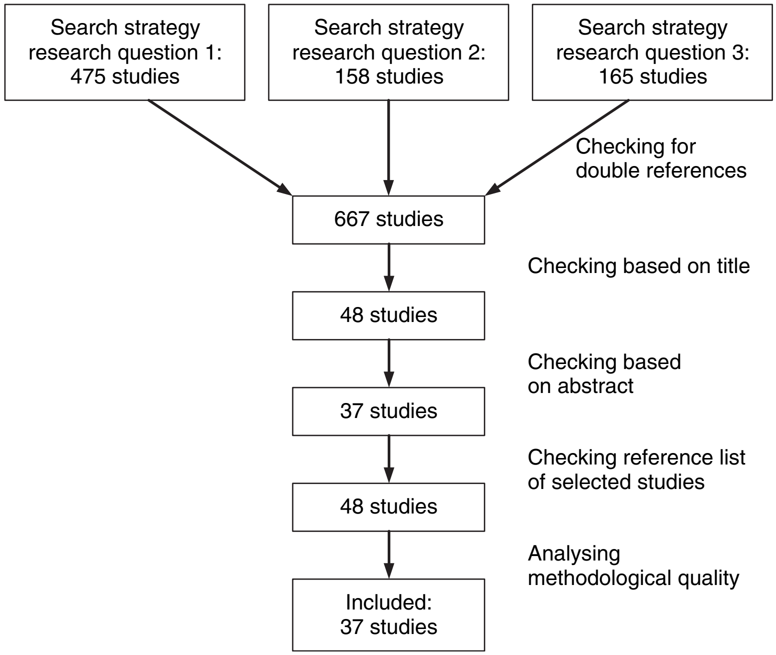

Figure 2 Results of the search process.

strength in transfemoral amputees. In all these studies strength was significantly lower in the amputated limb compared to the sound limb. According to Isakov *et al.*[20] the length of the stump influenced the changes in muscle strength. Subjects with a shorter stump (< 15.1 cm) had significant weaker muscles than subjects with a longer stump. No differences in strength were found between those who were amputated over seven years ago and those who were amputated more recently.[19] From these studies it was concluded that muscle force is reduced after amputation. Except for the study of Isakov *et al.*,[19] no data on the development of strength during rehabilitation was found (Table 4a).

Concerning (standing) balance, several authors[25–29] found deteriorated balance in amputees compared with healthy subjects. In addition, Hermodsson *et al.*[27] found a difference in balance between vascular and traumatic amputees at the same age. Geurts *et al.*[26] investigated the effect of balance and ambulation training on balance. A significant effect of training was found for standing balance with eyes closed and eyes open, expressed by body sway. In another paper by Geurts *et al.*[25] the balance control of amputees was significantly different from that of healthy subjects, during both single and dual tasks and both at the start and at the end of rehabilitation. However, between the start and the end of rehabilitation significant improvements were found in the amputation group during the dual-task condition but not during the single-task condition. Because the five studies are in agreement, there is strong evidence of deterioration of balance, especially for vascular amputees (Table 4a). Because only two studies were found, no strong evidence for the effect of training was found. However, from the two studies that were found, it looks like balance improves after training or rehabilitation but does not reach the levels seen in a comparable able-bodied population.

Status and development of walking ability

The success of amputees in regaining walking ability was investigated in different studies, with different results.[14,16,30–34] The total number of people with an amputation regaining walking ability (with or without walking aids such as crutches) varied from 56% to 97%, whereas the

Table 3 Overview of the included studies

	Purpose	Subjects[a,b]	Follow-up	Methods	Results	Score
Van Alste *et al.*[16]	Impression of cardiac condition	$N=39$, 10 TT, 11 TK, 13 TF & 5 Bi (67.4 years); V	—	Graded arm cranking test	Cardiac status poor, high WL_{max} & HR_{max} → result↑	8
Burger and Marincek[49]	Usability of functional tests in elderly amputees	$N=28$, 17 TT (67 ± 5.3 years), 11 TF (69 ± 7.2 years); V, T, Tu; $C=55$ H sedentary (70 ± 6.8 years)	—	Fullerton Functional Fitness Test & one-leg balance test	Amputees performed worse, level of amputation and activity influences outcome	5½
Bussmann *et al.*[35]	Advantage of HR or accelerometry in walking of amputees	$N=10$, 6 TT, 2 TK, 2 TF (64.6 ± 9.6 years); Un; C = 10 H (61.3 ± 11.4 years)	T1, T2 & T3 interval 1 month	Body motility, v_{walk} &%HRR measured during walking	Body motility & v_{walk} amputees <, %HRR >	9
Campbell and Ridler[50]	Prediction of prosthesis usage	$N=61$, 25 TT & 19 TF (median 79 years); V; 17 died before follow-up, level unknown	6–24 months after operation	5 specialists predicted prosthetic use and mobility before and after amputation	85% correctly predicted as user, 65% as non-user, comorbidities influence outcome	4½
Chakrabarty[51]	Relation quality of stumps and success of rehabilitation	$N=132$, 72 TT, 60 TF; Un	4 weeks, 3, 6, 12 months	Examination of stump and activity score	Better quality stumps → more mobile and active	3
Chin *et al.*[17]	Usability of one-leg cycling test for determining AT	$N=53$, 11 TT (35.6 years), 37 TF (51.8 years), 5 HD (40 years); Un	—	Graded exercise test monitoring gas exchange, ventilation and heart rate	Sign relation AT and predicted V_{O_2}max and AT and peak V_{O_2}	7½
Chin *et al.*[18]	Usability endurance training in improving physical fitness	$N=14$ (39.8 ± 12.4 years); $C=10$ (41.2 ± 18.4 years); all TF; T	6 weeks (at end of training)	Ergometer endurance training at target HR corresponding to AT point	AT and V_{O_2}max ↑ after training; no changes in control group	7
Chin *et al.*[13]	Cardiorespiratory endurance of physical fitness	$N=31$, 10 TT, 1 TK, 20 TF (26.0 ± 5.7 years); T; $C=18$ H (25.4 ± 3.7 years)	6 weeks	Incremental exercise test	V_{O_2}max, AT and WL_{max} amputees sign lower	8½
Chin *et al.*[52]	Usability% V_{O_2} max as indicator of physical fitness in predicting rehabilitation outcome	Success group: $n=8$ TF (72.2 ± 2.1); failure group: $n=9$ TF (63.2 ± 2.1); V	—	One-leg cycling test at self-selected maximum load	V_{O_2} max success group > failure group; age & age at amputation sign different between groups	6

Cruts *et al.*[14]	Relation cardiac load and rehabilitation	$N = 39$, 18 TT, 14 TK, 17 TF (72 years); V	—	Graded exercise test rowing	Peak workloads were low, related to result and indicator walking aids	8½
Dillingham *et al.*[53]	Use, satisfaction and problems with prosthetic devices	$N = 78$, 2.6% foot, 51.3% TT, 16.7% TK, 20.5% TF, 9% Bi; T	1 – >10 years	Medical records and follow-up interview data were collected	95% 80 h/week; 43% satisfied comfort; 25% problems stump; males higher use; pain and comorbidities ↓ satisfaction	4
Gallagher *et al.*[54]	Incidence, duration, intensity and interference of RLP and PLP with physical variables	$N = 104$, 51.0% TT, 42.3% TF, 5.8% Bi (45.3 ± 19.8 years); T, Co, Tu, other	—	Trinity Amputation and Prosthesis Experience Scales, questionnaire	48.1% RLP, 69.2% PLP; RLP = comorbidities; PLP = age, sex, level, cause and comorbidities	7½
Geurts *et al.*[26]	Balance restoration	$N = 10$, 4 TT, 2 TK, 2 TF, 2 drop-outs (67.7 ± 18.1 years); T, I, V; $C = 10$ H (65.6 ± 16.5 years)	3–14 weeks	Balance measured on forceplate before and after training	Postural control amputees < control group; No sign correlations activity score and body sway	9
Geurts *et al.*[25]	Dual task during balance	$N = 10$, 4 TT, 2 TK, 2 TF, 2 drop-outs (67.7 ± 18.1 years); T, I, V; $C = 10$ H (65.6 ± 16.5 years)	3–14 weeks	Balance measured on forceplate before and after training while performing dual-task	Dual-task performance improved sign over time	9½
Herbert *et al.*[36]	HR and Vo_2 during walking of children	$N = 10$, all TT (12.0 ± 3.4 years); $C = 14$ H (11.1 ± 3.0 years)	—	Vo_2, HR, PCI, %HR_{max} determined during walking	V_{walk}, HR amputees $= v_{walk}$, HR H, Vo_2 amputees >	9
Hermodsson *et al.*[55]	Gait performance traumatic vs vascular amputees vs healthy	$N = 12$ T (67 ± 9.9 years), $N = 12$ V (67 ± 10.6 years) all TT; $C = 12$ H	—	GRF, v_{walk}, questionnaires personal factors	V_{walk} amputees < healthy; no active forces during push-off vascular amputees	4½
Hermodsson *et al.*[27]	Postural function in standing	$N = 18$ V (68.8 ± 12.0 years), $N = 18$ T (63.9 ± 10.0 years), all TT, $C = 27$ H (69.6 ± 9.8 years)		Standing balance, 2 (open eyes/ blindfolded) and 1 (amputated/ sound (or right/ left for healthy) leg	2-leg: vascular sway >, trauma sway < (only with eyes open); 1-leg: standing time sign < for vascular	10

Table 3 (*Continued*)

	Purpose	Subjects[a,b]	Follow-up	Methods	Results	Score
Hoffman *et al.*[38]	Metabolic cost during walking	$N=5$ TF (22 ± 3 years); T, Co; $C=5$ H (22 ± 6)	—	HR, V_{O_2} and v_{walk} measured during walking	V_{walk} amputees 21% <, aerobic demands amputees 49–83% >	9
Isakov *et al.*[20]	Relation stump length, muscle atrophy and strength	$N=18$ TT (45.7 ± 14.7 years); T, V, Tu, I	—	Thigh girth, stump length and torque were measured	Strength amputees <, especially with short stump	10
Isakov *et al.*[19]	Muscle strength, related to time since amputation	$N=18$ TT (45.7 ± 14.7 years); Un	—	Muscle torques of knee extensors and flexors were measured	Strength amputated limb < sound limb; no effect of time	8½
Jaegers *et al.*[56]	Relation comfortable and efficient walking velocity	$N=11$ TF, T, osteo-sarcoma; $C=6$ H	—	HR, V_{O_2}, V_{CO_2}, respiratory coefficient, step rate and v_{walk} measured during walking	HR amputees > healthy; comfortable v_{walk} amputees < healthy; energy expenditure amputees > at same v_{walk}	4½
Jaegers *et al.*[37]	Prosthetic gait	$N=11$ TF (35.7 years); T, osteosarcoma; $C=2$ H	—	Walking on 10-m long conductive level floor area	Amputees: v_{walk} <, symmetry <; asymmetry related to stump length	7½
Jaegers *et al.*[57]	Insight in changes in hip muscles and bones	$N=12$, TF; T, osteosarcoma		MRI, 3D models	Higher amputation → more alterations and atrophy, esp. biarticular muscles	8½
Johnson *et al.*[44]	Mobility, age and comorbidities	$N=120$ TT (58 years); T, V, I	—	Retrospective chart review	Comorbidities, age and mobility correlated; no correlation cause and mobility	8½
Kegel *et al.*[58]	Effects of isometric muscle training on limb volume, strength and gait	$N=4$ TT (60.5 ± 9.7 years); T, V	2, 4, 6, 8 weeks	Isometric muscle training; limb volume, strength and gait evaluated	Limb volume, level of biofeedback and v_{walk} ↑; symmetry of gait ↓	5½
Klingenstierna *et al.*[21]	Muscle strength and functional ability	$N=8$ TT (61.5 years); T, V, Tu	8–12 weeks	Dynamometer; training; Isokin & isom strength, biopsies, functional ability	Peak torque ↑, cross-sectional area muscle fibers ↑, estimated walking ability ↑, use of walking aids ↓	8½
Kurdibaylo[59]	Evaluate motor capabilities and physical fitness	$N=147$, 52 TT; 56 TF, 19 TF +TT, 20 TF+TF; T; $C=30$	—	Examined in rest and wheelchair ergometer testing	Motor capabilities depend on capabilities of cardiac and respiratory system adjustment to limb loss	5½

MacKenzie *et al.*[30]	Functional outcome related to level of amputation	$N = 161$, 109 TT, 18 TK, 34 TF (35.2 ± 13.3 years); T	3, 6, 12, 24 months	SIP; pain, independence, v_{walk}, physician's satisfaction	TK: SIP scores, v_{walk}, independence < TT & TF; v_{walk} TT > TF	10
Marzoug *et al.*[60]	Assessment tool for prosthetic prescription	$N = 37$, 7 TT, 41 TF, 11 Bi (71 years); V, T, I, other	—	Amputees were examined by clinical team	14 proceed to definitive prosthesis; comorbidities main reason prosth rejection	5½
Matjacic and Burger[41]	Practising balance and postural control skills	$N = 14$ TT (49 ± 10 years); T	5 days	5 days, 20 min balance training; 1-leg balance test, TUGT, 10-m walk test	Performance in all three outcomes seemed to improve, only 10-m walk test sign ↑	9
McWhinnie *et al.*[31]	Rehabilitation outcome for 5 years after amputation	$N = 96$ (= 100 amp), 67 TT (75 years), 14 TK (78 years), 19 TF (76 years)	1, 2, 3, 4, 5 years	Clinical review	Over time: prosthetic use & walking ability ↓; stump problems & comorbidities influences prosthetic fitting	8
Melchiorre *et al.*[45]	Functional status of traumatic and vascular amputees	$N = 24$, T: 7 TT, 5 TF; V: 9 TT, 3 TF	±31 days	Chart review; FIM scores at admission and discharge	Vascular: older + greater stump comorbidity; comorb. correlated with FIM scores	6½
Miller and Deathe[28]	Changes in balance confidence scores	$N = 245$, 68% TT, 32% TF (incl. TK); T, V	2 years	Chart review, postal survey; ABC-scale	No diff. ABC over time; age, comorbidities, walking automatism, aids and depression related to ABC	8½
Miller *et al.*[42]	Relationship falling and balance confidence on mobility capability, performance and social activity	$N = 435$, 73% TT, 27% TF (incl. TK) (62 ± 15.7 years); T, V	—	Chart review, survey questionnaire; ABC-scale, Mobility capability, mobility performance, social activity	ABC score sign. associated with mobility capability, performance and social activity	7
Moirenfeld *et al.*[22]	Isokinetic strength and endurance of knee extensors and flexors	$N = 11$ TT (43.7 ± 14.4 years); T	—	Dynamometer; torque, angle, peak torque (PT), fatigue index	PT amp. limb sign. < sound limb; fatigue index amp. limb sign. > sound limb for flexion	7
Mueller and Delitto[46]	Criteria contributing to successful prosthetic use	$N = 56$, 38 TT, 18 TF; V	2.2 (SD ± 1.26) years	Chart review; telephone survey	TT sign. often successful; sign. diff. compliance + med. problems successful and unsuccessful in AK group	8½

Table 3 (*Continued*)

	Purpose	Subjects[a,b]	Follow-up	Methods	Results	Score
Munin *et al.*[32]	Predictors of successful prosthetic ambulation	$N=75$, 71% TT; T, V, Tu	—	Chart review	Sign. relation absence of residual-limb contracture and longer length of stay and success; younger age modestly correlated	8½
Nadollek *et al.*[4]	Relationship weight distribution, strength of hip abductor muscles and gait parameters	$N=22$ TT; V	—	Balance, strength, gait measurements; level of function, prosthetic use, medical history; pain	Sign. more weight on sound limb; strong hip abductor muscles correlated with weight-bearing amputated limb and gait parameters	9½
Pernot *et al.*[33]	Demographic characteristics, cause, level, functional level	$N=153$ (=180 amp), 82 TT, 43 TK, 55 TF (±69 years); T, V, other; Follow up: $N=87$	1 years	Chart review, interview	Majority have low walking skills, walking distance limited, ADL-dependent, limited by amputation	8
Pohjolainen[48]	Basic parameters of classification for stump	$N=155$, 93 TT, 62 TF; V, T, Tu, frostbite, I	1 years	Stump classified; relation stump variables and walking functions evaluated	Phantom pain and stump pain had a relationship with reduced walking distance and reduced outdoor walking	4
Pohjolainen and Alaranta[47]	Pre- and postoperative factors affecting functional ability and social situation	$N=155$, 93 TT, 62 TF (63 years); T, V, Tu, other	1 years	Chart review, interview, examination	Association age and walking distance and time, outdoor walking, aids and prosthetic use; stump pain & PLP → ↓ outdoor walking and walking distance; > stump length → ↑ walking distance	10
Renstrom *et al.*[23]	Reduction of thigh muscle strength	$N=32$ TT (men (n = 24) 61±18 years, women (n = 8) 38±9 years); T, V, Tu, I	—	Dynamometer, isometric and isokinetic strength; biopsy; cross-sectional area; stump and gait determinants	Strength and circumference amp. Limb < sound limb; strength vasc. amp. < trauma; strength amp. limb sign. correlated step length, max v_{walk}, circumference thigh	8½
Ryser *et al.*[24]	Hip abductor strength	$N=10$ TF (41.4±12.5 years), T, V, Tu; $C=10$ H (41.5±15.0 years)	—	Physical examination, dynamometer	Amp. limb abduction torque 30% < sound limb; no sign differences sound and control limb	8

Schoppen *et al.*[43]	Physical, mental and social predictors of functional outcome	$N = 46$, 33 TT, 8 TK, 5 TF; V	2, 6 weeks, 6, 12 months	Physical, mental and social characteristics, development of functional capabilities, functional outcome parameters	Low functional level and prosthetic use; predictors functional outcome: age at amputation, one-leg balance on unaffected limb, cognitive impairment and probably comorbidity	7½
Sjödahl *et al.*[39]	Evaluating effect new training approach on gait	$N = 9$ TF (33 years), T, Tu	Before, after training, 6 months	Training combining physiotherapy and psychological awareness (mean 10 months); gait parameters	After training: sign. increase v_{walk}, gait more symmetric, no walking-aids needed; no secondary low-back pain	6½
Sjödahl *et al.*[40]	Effect of training on temporal parameters, movements, moment and power	$N = 9$ TF (33 years), T, Tu; $C = 9$ H (36 years)	Before, after training, 6 months	Gait-training programme; 3D gait analysis	Sign. increase in gait speed, cadance and step length both legs after training and at follow-up	8½
Summers *et al.*[61]	Foot loading and area of stability reflecting clinical improvement	$N = 10$, 4 TT, 2 TK, 3 TF, 1 HD (66 years); Un	9 days–3 weeks	Forceplate; weight-bearing and distribution; clinical assessments	Weight-bearing prosthetic foot ↑; Walking ability during rehab. ↑	8½
Viton *et al.*[29]	Equilibrium and movement control strategies	$N = 5$ TT (34.8 years); T; $C = 5$ H	—	Balance test; optoelectronic system, forceplate, EMG	Amp. more trials imbalanced for both amp. and sound limb	7½

[a]N, number of subjects; TT, transtibial amputation; TK, through-knee amputation; TF, transfemoral amputation; HD, hip disarticulation; Bi, bilateral; C, number of controls; H, healthy.
[b]Cause of amputation: T, traumatic; V, vascular; Tu, tumour; I, infection; Co, congenital; Un, unknown.
V_{walk}, walking velocity; AT, aerobic threshold; $V{O_2}max$, maximum oxygen uptake; RLP, residual limb pain; PLP, phantom limb pain; TUGT, Timed Up and Go Test; ABC-scale, Activities-specific Balance Confidence Scale; HR, heart rate; % HRR, percentage heart rate reserve; PCI, physiological cost index; WL, workload; SIP, Sickness Impact Profile; FIM, Functional Independence Measure.

Table 4a Overview of evidence for the status and development of physical capacity

	Van Alste *et al.*[16]	Chin *et al.*[18]	Chin *et al.*[13]	Cruts *et al.*[14]	Geurts *et al.*[26]	Geurts *et al.*[25]	Hermodsson *et al.*[27]	Isakov *et al.*[20]	Isakov *et al.*[19]	Klingenstierna *et al.*[21]	Miller and Deathe[28]	Moirenfeld *et al.*[22]	Renstrom *et al.*[23]	Ryser *et al.*[24]	Viton *et al.*[29]	Evidence[a]
Status																
Aerobic capacity	+/−		+	+												Insufficient
Anaerobic capacity																None
Muscle force								+	+	+		+	+	+		Strong
Flexibility																None
Balance					+	+	+				+				+	Strong
Development																
Aerobic capacity		+	+													Insufficient
Anaerobic capacity																None
Muscle force									−							None
Flexibility																None
Balance					+	+										Insufficient

percentage of outdoor walkers varied from 26% to 62%. Of all walkers, over 80% used walking aids. The differences in the success of regaining walking ability between the studies was most likely the result of different populations. In most studies older (age > 60 years) vascular amputees participated. Although it cannot be discerned with certainty, in those studies where traumatic and/or younger amputees participated, higher levels of walking ability seemed to be reached. Additionally, in different studies the criteria for outdoor walking and use of walking aids were different. Hence, comparison of the results of the different studies on regaining walking ability was difficult.

The development of walking ability can be described by temporal and spatial characteristics such as walking velocity and symmetry. Strong evidence was found for a decrease in walking velocity of amputees compared with healthy subjects (Table 4b). Three studies were in agreement on the finding of a lower walking velocity after amputation.[35–37] Hoffman *et al.*[38] found no differences in walking speed between bilateral trans-femoral amputees and healthy subjects. However, when walking speeds were compared without inclusion of one amputee outlier and her matched control a significant difference in walking speed was found ($P = 0.0004$). No relevant studies about the effect of training on walking velocity were found.

Some statistical differences in symmetry after amputation were found. In the study of Jaegers *et al.*[37] a more asymmetrical gait pattern was found in transfemoral amputees than in healthy subjects. In the studies of Sjödahl *et al.*[39,40] an asymmetrical gait pattern was found in transfemoral amputees 10 years after amputation. Gait pattern after transfemoral amputation was asymmetrical according to these three studies.[37,39,40] Evidence for a decreased symmetry of the gait pattern was therefore sufficient. No sufficient evidence was found on the development of the symmetry over time or with training (Table 4b).

Relationship between physical capacity and walking ability

No information was found about the influence of anaerobic capacity and flexibility on walking ability. The relationship between walking ability

Table 4b Overview of evidence for the status and development of walking ability

	Bussmann *et al.*[35]	Herbert *et al.*[36]	Hoffman *et al.*[38]	Jaegers *et al.*[37]	Sjödahl *et al.*[39]	Sjödahl *et al.*[40]	Evidence
Status							
V_{walk}	+	+	+/−	+			Strong
Symmetry				+	+	+	Strong
Development							
V_{walk}							None
Symmetry					+	+	Insufficient

Table 4c Overview of evidence for a relation between physical capacity and walking ability

	Van Alste *et al.*[16]	Cruts *et al.*[14]	Geurts *et al.*[26]	Hermodsson *et al.*[27]	Hoffman *et al.*[38]	Klingenstierna *et al.*[21]	Matjacic and Burger[41]	Miller *et al.*[42]	Nadollek *et al.*[54]	Renstrom *et al.*[23]	Ryser *et al.*[24]	Schoppen *et al.*[43]	Evidence
WA & Acap	+/−	+											Insufficient
WA& An													None
WA & Mf						+/− [b]			+	+	+/−		Insufficient
WA & F													None
WA & Bal			−	−			+ [b]	+				+ [b]	Strong

[a]Assessment of evidence was based on both the number of studies and the availability of prospective studies. To be labelled strong at least three studies should be available of which at least 70% should be in agreement.
[b]Study with a prospective design.
V_{walk}, walking velocity; WA, walking ability; Acap, aerobic capacity; An, anaerobic capacity; Mf, muscle force; F, flexibility; Bal, balance.

and aerobic capacity was investigated by Van Alste *et al.*[16] and Cruts *et al.*[14] Van Alste *et al.*[16] showed that the mean performances of unilateral, vascular amputees during a graded exercise rowing test were significantly different for subjects who achieved prosthetic walking level 2 (walking with the help of a walking frame, less than 40 m and only indoors) from those who achieved level 3 (walking with or without the use of a walking stick or crutches, for more than 40 m and also outdoors) ($P < 0.05$). The mean maximum heart rates were 113 ± 7 and 130 ± 4 beats/min respectively. Their mean maximum work loads were 44 ± 3 and 71 ± 4 W respectively. However, from the results of the study it remained unclear whether this difference was influenced by medication use of the subjects. Cruts *et al.*[14] also stated that the maximum workload influences the walking ability. Those who had a maximum workload over 45 W during a graded exercise rowing test were more likely to walk without a walking frame than those who had a maximum workload lower than 45 W. Workload was not influenced by the use of medication in this study. Although these studies indicated a relation between aerobic capacity and (the development of) walking ability, no strong evidence was found. No causative relation could be assumed because no prospective data were available (Table 4c).

A relation between walking ability and muscle force was found by different authors.[5,21,23,24] Renstrom *et al.*[23] found a positive effect of strength in the amputated limb on the walking velocity and an effect on step length. Klingenstierna *et al.*,[21] however, did not find a difference in walking velocity after training strength of both legs, but did find a significant increase of maximum walking distance. From the study of Nadollek *et al.*[5] it became clear that strong hip muscles were correlated with increased weight-bearing on the amputated limb, improved gait parameters (cadance, gait cycle, velocity, step length and stride length) and reduced centre of pressure exertion under the amputated limb. According to Ryser *et al.*[24] mean isometric abductor strength on the amputated side was significantly greater in people who ambulate without canes than in people who frequently use canes. Although all these studies investigated the relation between strength and walking ability, the relationship remained unclear because all studies focused on different parameters of walking ability. Only velocity of walking was mentioned in three studies. However, because the results of these studies were not in agreement, it is concluded that the relationship between muscle force and walking ability remains arbitrary (Table 4c).

Matjacic and Burger,[41] Miller *et al.*[42] and Schoppen *et al.*[43] found a positive relationship between balance and walking ability. However, in the study of Matjacic and Burger[41] this effect was only seen on the 10-m walk test but not on the Timed Up and Go Test. According to Schoppen *et al.*[43] one-leg balance on the unaffected limb could help to predict functional outcome (Table 3). In contrast, in the study of Geurts *et al.*[26] no significant relationship between the activity score (scored with a functional activity questionnaire) and balance (expressed as body sway) was found. In the study of Hermodsson *et al.*[27] also no relationship was found. The development of walking ability is strongly related to balance, because the studies of Matjacic and Burger[41] and Schoppen *et al.*[43] were prospective (Table 4c). Regaining walking ability could be influenced by the amount of balance.[43]

Disease characteristics and personal factors

As can be seen from the Results section, different disease characteristics and personal factors influence both physical capacity and walking ability and hence act as confounding variables when assessing the relation between physical capacity and walking ability. This could especially be true for causes of amputation, comorbidities and age (Figure 1).

No direct influence on the functional outcome was found for the cause of amputation.[44,45] However, when the numbers of walkers in the different studies were compared, higher levels of walking ability seemed to be reached for traumatic amputees than for vascular amputees.[14,16,30–34] On muscle strength, Isakov *et al.*[20] found an effect of cause of amputation. Strength was significantly lower in vascular amputees than in traumatic amputees.

According to different authors[14,32,33,43–47] a positive relation between the absence of comorbidities of the whole body and walking ability exists. Comorbidities (vascular diseases) have also been shown to affect aerobic capacity.[14]

It is known that age influences physical capacity.[15] Strong evidence was found for a positive relation between walking ability and younger age.[31,32,43,44,47] According to Schoppen *et al.*[43] age at amputation could even help to predict functional outcome. In the study of Melchiorre *et al.*[45] the vascular amputees seemed to be significantly older than the traumatic amputees but no differences in functional outcome were found. Jaegers *et al.*[37] did not find a correlation between comfortable walking speed and age.

Discussion

The purpose of the study was to review the literature on the physical capacity and walking ability of amputees and to investigate the influence of physical capacity on regaining walking ability and on the development of walking ability. The first research question concerned the status and development of physical capacity, expressed by aerobic capacity, anaerobic capacity, muscle force, flexibility and balance. Strong evidence was found for a deteriorated status of muscle strength and balance after amputation. Insufficient evidence was found about the status of the other parameters of physical capacity. The second research question dealt with the status and development of walking ability. The percentage of amputees who regained walking ability varied from 56% to 97%, of whom more than 80% of the walkers needed walking aids such as crutches. The status of walking velocity and symmetry decreased after amputation, but on development no strong evidence was available.

The last research question combined the former two research questions and therefore investigated the relationship between physical capacity and walking ability. Strong evidence was found for a relation between balance and development of walking ability, whereas the relation between walking ability and aerobic capacity and walking ability and muscle strength remained more arbitrary. According to Schoppen *et al.*[43] balance not only influences the development of walking ability but can also predict the regaining of walking ability.

Because balance deteriorates after amputation and better balance was related to better walking ability and possibly to the regaining of walking ability, it could be concluded that training of balance during the rehabilitation process is useful. However, no intervention studies or clinical trials are available and no indisputable evidence of the effect of training on balance was found. Although the relation between walking ability and aerobic capacity and between walking ability and muscle strength remained somewhat arbitrary, training of aerobic capacity and muscle strength should not be discouraged. Muscle strength deteriorates in amputees and from a theoretical point of view training this parameter could be beneficial. For aerobic capacity no indisputable evidence was found in this study, but there seemed to be some indication that aerobic capacity decreased after amputation and improved after training. However, more research is necessary to elucidate their relation to walking ability.

Although 48 studies were found, of which 37 had sufficient quality and were involved in this review, strong consistent evidence was only found for a relation between balance and walking ability. The main reason for this lack of evidence was a lack of literature in general and a lack of prospective, longitudinal data especially. Most studies were performed with a cross-sectional descriptive design from which no causal relationship could be derived. Besides, in about half of the studies there was only a small number of participants, which influences the power, reliability and generalizability of the results of these studies. In addition different definitions of parameters of walking ability were used, which made the comparison of the different studies difficult. In some cases where there were enough studies, for example for the relationship between muscle strength and walking ability, no evidence was found because of contradictory results between the different studies, possibly because of different subjects and designs used.

As can be seen from the Results section, different disease characteristics and personal factors influence physical capacity and walking ability and hence act as confounding variables when assessing the relation between physical capacity and walking ability. The interaction between these different parameters is unknown. For example, Melchiorre *et al.*[45] stated that vascular amputees had significantly more stump comorbidities than traumatic amputees. Geertzen *et al.*[6] and Waters and Mulroy[8] stated that vascular amputees had more walking problems than traumatic amputees. In addition it is known that vascular amputees in general are older than traumatic amputees and age also affects physical capacity.[15] The results of Pohjolainen[48] showed that stump problems had a relationship with reduced walking ability. However, some of the subjects in Pohjolainen's study[48] were amputated because of vascular problems. Hence, it remains unclear whether the walking problems were the result of stump problems, the cause of amputation or of older age. These confounding interactions make it difficult to interpret and compare the results of the different studies, especially since in most studies no distinctions were made based on level and cause of amputation.

Limitations of the review

Limitations can not only be found in the available literature but also in the current review. At first it should be noted that only one author assessed the methodological quality of the studies. Because of that, no inter-rater reliability could be assessed and the scoring remained somewhat subjective. In addition, no clear cut-off point is known for the checklist for statistical review of general papers (adapted from Gardner and Altman[11]). In the current review the cut-off point was chosen at 60%, according to Kaper *et al.*[12] Second, all items on the scoring list were equally judged and counted once. Maybe some items are more important than other items. For example, the design of the study may be important. Most

Clinical messages

- There is sufficient evidence that muscle strength, balance and walking ability deteriorate after lower limb amputation.
- The restoration of walking ability is affected by balance.
- The influence of the other factors of physical capacity remains unclear.

studies used in this review did not have a prospective design but still scored high. Another checklist could have led to somewhat different results concerning the quality of the studies and therefore to other results concerning the research questions. Finally, it should be noted that walking after lower limb amputation is a multidimensional problem in which many different aspects can influence the outcome. To limit the scope of the review, only the relation between physical capacity and walking ability was investigated. In addition, some disease characteristics and personal factors were taken into account. Other possible aspects, such as external factors, were not included and are therefore missing in the results. To complete the puzzle on walking ability after lower limb amputation all aspects should be included.

Recommendations

In this review it became clear that the walking ability of amputees could be influenced by many different underlying mechanisms. Despite the relatively large number of studies found, completely reliable and consistent information about these mechanisms is lacking. Therefore it is recommended that more prospective intervention studies on the walking ability of amputees should be carried out. Taking into account the multifactorial nature of the issue, to get unambiguous results walking ability should be adequately defined at first. Also, the possible confounders should be controlled as closely as possible and comparisons based on cause of amputation should be made. Based on the results of these future studies, the rehabilitation process could be more closely focused on specific items. Until more results are known, it is recommended to continue to train aerobic capacity, balance and muscle strength as well as functional walking ability during the rehabilitation process of amputees in order to regain a certain amount of physical capacity and to improve walking ability.

Competing interests

None declared.

Contributors

JvV initiated the study, designed the study, wrote the paper, scored methodological quality and was guarantor. HH initiated the study, designed the study, monitored progress and contributed to the discussion of the results. LvdW designed the study, monitored progress and contributed to the discussion of the results. HS, WP and CvB Monitored progress and contributed to the discussion of the results.

References

1 Rommers GM. *The elderly amputee: rehabilitation and functional outcome*. Rijksuniversiteit Groningen, 2000.
2 Blumentritt S, Schmalz T, Jarasch R. [Significance of static prosthesis alignment for standing and walking of patients with lower limb amputation]. *Orthopade* 2001; **30**: 161–68.
3 Culham EG, Peat M, Newell E. Below-knee amputation: a comparison of the effect of the SACH foot and single axis foot on electromyographic patterns during locomotion. *Prosthet Orthot Int* 1986; **10**: 15–22.
4 Nadollek H, Brauer S, Isles R. Outcomes after trans-tibial amputation: the relationship between quiet stance ability, strength of hip abductor muscles and gait. *Physiother Res Int* 2002; **7**: 203–14.
5 Fisher SV, Gullickson G, Jr. Energy cost of ambulation in health and disability: a literature review. *Arch Phys Med Rehabil* 1978; **59**: 124–33.
6 Geertzen JH, Martina JD, Rietman HS. Lower limb amputation. Part 2: Rehabilitation – a 10 year literature review. *Prosthet Orthot Int* 2001; **25**: 14–20.
7 Pinzur MS. Gait analysis in peripheral vascular insufficiency through-knee amputation. *J Rehabil Res Dev* 1993; **30**: 388–92.
8 Waters RL, Mulroy S. The energy expenditure of normal and pathologic gait. *Gait Posture* 1999; **9**: 207–31.
9 Moore EG, Durstine JL, Marsh AP. Chapter 2: Framework. In Durstine JL, Moore GE eds. *ACSM's exercise management for persons with chronic diseases and disabilities*. Human Kinetics, 2003.
10 World Health Organization. *International classification of functioning, disability and health* (ICF). WHO, 2002.
11 Gardner MJ, Altman DG. *Statistics with confidence: confidence intervals and statistical guidelines*. British Medical Journal, 1989.
12 Kaper J, Woude van der LHV, Tulder van MW. Traumatisch hersenletsel en arbeidsreïntegratie: Een systematisch literatuuronderzoek naar de

voorspellende determinanten bij mensen met een hersenkneuzing. *TSG* 2003; **81**: 71–78.
13 Chin T, Sawamura S, Fujita H *et al*. Physical fitness of lower limb amputees. *Am J Phys Med Rehabil* 2002; **81**: 321–25.
14 Cruts HE, Vries de J, Zilvold G, Huisman K, Alste van JA, Boom HB. Lower extremity amputees with peripheral vascular disease: graded exercise testing and results of prosthetic training. *Arch Phys Med Rehabil* 1987; **68**: 14–19.
15 Wilmore JH, Costill DL. *Physiology of sport and exercise*. Human Kinetics, 1999.
16 Alste van JA, Cruts HE, Huisman K, Vries de J. Exercise testing of leg amputees and the result of prosthetic training. *Int Rehabil Med* 1985; **7**: 93–98.
17 Chin T, Sawamura S, Fujita H *et al*. The efficacy of the one-leg cycling test for determining the anaerobic threshold (AT) of lower limb amputees. *Prosthet Orthot Int* 1997; **21**: 141–46.
18 Chin T, Sawamura S, Fujita H *et al*. Effect of endurance training program based on anaerobic threshold (AT) for lower limb amputees. *J Rehabil Res Dev* 2001; **38**: 7–11.
19 Isakov E, Burger H, Gregoric M, Marincek C. Isokinetic and isometric strength of the thigh muscles in below-knee amputees. *Clin Biomech* 1996; **11**: 232–35.
20 Isakov E, Burger H, Gregoric M, Marincek C. Stump length as related to atrophy and strength of the thigh muscles in trans-tibial amputees. *Prosthet Orthot Int* 1996; **20**: 96–100.
21 Klingenstierna U, Renstrom P, Grimby G, Morelli B. Isokinetic strength training in below-knee amputees. *Scand J Rehabil Med* 1990; **22**: 39–43.
22 Moirenfeld I, Ayalon M, Ben-Sira D, Isakov E. Isokinetic strength and endurance of the knee extensors and flexors in trans-tibial amputees. *Prosthet Orthot Int* 2000; **24**: 221–25.
23 Renstrom P, Grimby G, Larsson E. Thigh muscle strength in below-knee amputees. *Scand J Rehabil Med Suppl* 1983; **9**: 163–73.
24 Ryser DK, Erickson RP, Cahalan T. Isometric and isokinetic hip abductor strength in persons with above-knee amputations. *Arch Phys Med Rehabil* 1988; **69**: 840–45.
25 Geurts AC, Mulder TW, Nienhuis B, Rijken RA. Dual-task assessment of reorganization of postural control in persons with lower limb amputation. *Arch Phys Med Rehabil* 1991; **72**: 1059–64.
26 Geurts AC, Mulder TW, Nienhuis B, Rijken RA. Postural reorganization following lower limb amputation. Possible motor and sensory determinants of recovery. *Scand J Rehabil Med* 1992; **24**: 83–90.
27 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. *Prosthet Orthot Int* 1994; **18**: 150–58.
28 Miller WC, Deathe AB. A prospective study examining balance confidence among individuals with lower limb amputation. *Disabil Rehabil* 2004; **26**: 875–81.
29 Viton JM, Mouchnino L, Mille ML *et al*. Equilibrium and movement control strategies in trans-tibial amputees. *Prosthet Orthot Int* 2000; **24**: 108–16.
30 MacKenzie EJ, Bosse MJ, Castillo RC *et al*. Functional outcomes following trauma-related lower-extremity amputation. *J Bone Joint Surg Am* 2004; **86-A**: 1636–45.
31 McWhinnie DL, Gordon AC, Collin J, Gray DW, Morrison JD. Rehabilitation outcome 5 years after 100 lower-limb amputations. *Br J Surg* 1994; **81**: 1596–99.
32 Munin MC, Espejo-De Guzman MC, Boninger ML. Predictive factors for successful early prosthetic ambulation among lower-limb amputees. *J Rehabil Res Dev* 2001; **38**: 379–84.
33 Pernot HF, Winnubst GM, Cluitmans JJ, Witte de LP. Amputees in Limburg: incidence, morbidity and mortality, prosthetic supply, care utilisation and functional level after one year. *Prosthet Orthot Int* 2000; **24**: 90–96.
34 Schoppen T, Boonstra A, Groothoff JW, Vries de J, Goeken LNH, Eisma WH. Relationship between impairments, activities, and participation in lower limb amputee patients; In Schoppen T ed. *Functional outcome after a lower limb amputation*. Rijksuniversiteit Groningen, 2002: 41–58.
35 Bussmann JBJ, Berg-Emons van den HJG, Angulo SM, Stijnen T, Stam HJ. Sensitivity and reproducibility of accelerometry and heart rate in physical strain assessment during prosthetic gait. *Eur J Appl Physiol* 2004; **91**: 71–78.
36 Herbert LM, Engsberg JR, Tedford KG, Grimston SK. A comparison of oxygen consumption during walking between children with and without below-knee amputations. *Phys Ther* 1994; **74**: 943–50.
37 Jaegers SM, Arendzen JH, Jongh de HJ. Prosthetic gait of unilateral transfemoral amputees: a kinematic study. *Arch Phys Med Rehabil* 1995; **76**: 736–43.
38 Hoffman MD, Sheldahl LM, Buley KJ, Sandford PR. Physiological comparison of walking among bilateral above-knee amputee and able-bodied subjects, and a model to account for the differences in metabolic cost. *Arch Phys Med Rehabil* 1997; **78**: 385–92.

39 Sjodahl C, Jarnlo G-B, Persson BM. Gait improvement in unilateral transfemoral amputees by a combined psychological and physiotherapeutic treatment. *J Rehabil Med* 2001; **33**: 114–18.

40 Sjodahl C, Jarnlo G-B, Persson BM. Kinematic and kinetic gait analysis in the sagittal plane of trans-femoral amputees before and after special gait re-education. *Prosthet Orthot Int* 2002; **26**: 101–12.

41 Matjacic Z, Burger H. Dynamic balance training during standing in people with trans-tibial amputation: a pilot study. *Prosthet Orthot Int* 2003; **27**: 214–20.

42 Miller WC, Deathe AB, Speechley M, Koval J. The influence of falling, fear of falling, and balance confidence on prosthetic mobility and social activity among individuals with a lower extremity amputation. *Arch Phys Med Rehabil* 2001; **82**: 1238–44.

43 Schoppen T, Boonstra A, Groothoff JW, Vries de J, Goeken LN, Eisma WH. Physical, mental, and social predictors of functional outcome in unilateral lower-limb amputees. *Arch Phys Med Rehabil* 2003; **84**: 803–11.

44 Johnson VJ, Kondziela S, Gottschalk F. Pre and post-amputation mobility of trans-tibial amputees: correlation to medical problems, age and mortality. *Prosthet Orthot Int* 1995; **19**: 159–64.

45 Melchiorre PJ, Findley T, Boda W. Functional outcome and comorbidity indexes in the rehabilitation of the traumatic versus the vascular unilateral lower limb amputee. *Am J Phys Med Rehabil* 1996; **75**: 9–14.

46 Mueller MJ, Delitto A. Selective criteria for successful long-term prosthetic use. *Phys Ther* 1985; **65**: 1037–40.

47 Pohjolainen T, Alaranta H. Predictive factors of functional ability after lower-limb amputation. *Ann Chir Gynaecol* 1991; **80**: 36–39.

48 Pohjolainen T. A clinical evaluation of stumps in lower limb amputees. *Prosthet Orthot Int* 1991; **15**: 178–84.

49 Burger H, Marincek C. Functional testing of elderly subjects after lower limb amputation. *Prosthet Orthot Int* 2001; **25**: 102–107.

50 Campbell WB, Ridler BM. Predicting the use of prostheses by vascular amputees. *Eur J Vasc Endovasc Surg* 1996; **12**: 342–45.

51 Chakrabarty BK. An audit of the quality of the stump and its relation to rehabilitation in lower limb amputees. *Prosthet Orthot Int* 1998; **22**: 136–46.

52 Chin T, Sawamura S, Fujita H *et al*. %VO2max as an indicator of prosthetic rehabilitation outcome after dysvascular amputation. *Prosthet Orthot Int* 2002; **26**: 44–49.

53 Dillingham TR, Pezzin LE, MacKenzie EJ, Burgess AR. Use and satisfaction with prosthetic devices among persons with trauma-related amputations: a long-term outcome study. *Am J Phys Med Rehabil* 2001; **80**: 563–71.

54 Gallagher P, Allen D, Maclachlan M. Phantom limb pain and residual limb pain following lower limb amputation: a descriptive analysis. *Disabil Rehabil* 2001; **23**: 522–30.

55 Hermodsson Y, Ekdahl C, Persson BM, Roxendal G. Gait in male trans-tibial amputees: a comparative study with healthy subjects in relation to walking speed. *Prosthet Orthot Int* 1994; **18**: 68–77.

56 Jaegers SM, Arendzen JH, Jongh de HJ. The relationship between comfortable and most metabolically efficient walking speed in persons with unilateral above-knee amputation. *Arch Phys Med Rehabil* 1993; **74**: 521–25.

57 Jaegers SM, Arendzen JH, Jongh de HJ. Changes in hip muscles after above-knee amputation. *Clin Orthop Relat Res* 1995; **319**: 276–84.

58 Kegel B, Burgess EM, Starr TW, Daly WK. Effects of isometric muscle training on residual limb volume, strength, and gait of below-knee amputees. *Phys Ther* 1981; **61**: 1419–26.

59 Kurdibaylo SF. Cardiorespiratory status and movement capabilities in adults with limb amputation. *J Rehabil Res Dev* 1994; **31**: 222–35.

60 Marzoug EA, Landham TL, Dance C, Bamji AN. Better practical evaluation for lower limb amputees. *Disabil Rehabil* 2003; **25**: 1071–74.

61 Summers GD, Morrison JD, Cochrane GM. Amputee walking training: a preliminary study of biomechanical measurements of stance and balance. *Int Disabil Stud* 1988; **10**: 1–5.