Predicting Running Ability After Lower Extremity Amputation: A Review

Rebecca Dutton, MD

Department of Orthopaedics & Rehabilitation, The University of New Mexico Health Sciences Center, Albuquerque, New Mexico

Corresponding Author Rebecca Dutton, MD. Department of Orthopaedics & Rehabilitation, MSC 10 5600, 1 University of New Mexico, Albuquerque, NM 87103 (email: radutton@salud.unm.edu).

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ABSTRACT

The ability to ambulate with a prosthesis after lower extremity limb loss is an important determinant of functional independence and quality of life. Some individuals may be capable of achieving higher levels of mobility (eg, running) that can further improve function, physical health, and mental health. Thus, a fundamental understanding of the variables that help predict ambulation ability after lower limb loss is important. Particular attention should be given to modifiable predictors, as interventions directed at these conditions can help facilitate optimal mobility and function. This article reviews various factors that influence the ability to both walk and run after lower extremity limb loss.

Keywords: Amputation, Lower Extremity, Walking, Running

INTRODUCTION

The ability to ambulate with a prosthesis after lower extremity limb loss is an important determinant of functional independence and quality of life. It has been suggested that the ability to walk with a prosthesis has the greatest influence on predicting quality of life in patients undergoing lower limb amputation due to peripheral vascular disease.[1] Studies reveal improved coping mechanisms, mood, and self-esteem with higher levels of physical activity after amputation.[2,3]

Owing to advances in prosthetic science, running may be achievable for some individuals after lower extremity amputation. Higher levels of physical activity may further enhance function and return to preinjury lifestyle, with important implications for chronic disease risk reduction. This may be of particular significance in amputees, who generally demonstrate higher rates of cardiovascular disease and diabetes mellitus.[4,5] Even so, individuals with lower extremity limb loss tend to be less active than their able-bodied counterparts.[6]

It is critical that practitioners know what elements influence successful mobility after amputation. It is especially important to recognize and address the modifiable factors to maximize ambulatory potential. Therefore, the present article aims to review the predictors of independent walking and running after major lower extremity amputation, defined as amputation above the level of the ankle. Although prosthetic design can be important to enhance performance and endurance, specialized prostheses (eg, running-specific prostheses) are not an independent determinant of the ability to run after amputation and are beyond the scope of this review.

Predictors of Walking After Lower Extremity Amputation

In the current context, the proverbial phrase "we must learn to walk before we can run" rings true. Before considering those predictive factors for running after lower extremity limb loss, it is important to understand the various circumstances that influence ambulation potential with a prosthesis. Broadly, these factors may be categorized into three groups: 1) personal or intrinsic characteristics, 2) residual limb qualities, and 3) systems of care (Figure 1).

Intrinsic Characteristics

Fitness and pre-amputation ability to ambulate are two of the greatest predictors for walking with a prosthesis after amputation.[7] Patient fitness as assessed by VO2 max (ie, maximal oxygen uptake during exercise) has been associated with the ability to walk with a prosthesis. Three studies from the same research group evaluated sets of elderly patients with transfemoral amputations.[8-10] These studies measured VO2 max while participants performed a single-leg cycling exercise with the intact limb, and they found that higher pre-rehabilitation VO2 max was correlated with successful prosthetic ambulation. This gives patients the ability to walk at least 100 meters with or without a cane. Ultimately, the authors concluded that a VO2 max of at least 50% may be a valid threshold to predict successful ambulation with a prosthesis.[8-10]

In a similar vein, pre-amputation independent walking has been correlated with walking ability post-amputation. One study of dysvascular amputees found that the ability to walk alone outdoors before amputation was a primary predictor of walking with a prosthesis after amputation.[11] A second study

Table 1. A proposed residual limb quality grading scale

Residual Limb Characteristic			Points
Wound	Healed	+10	
	Unhealed	-5	
	Infected	-10	
Edema	None	+10	
	Minimal	+5	
	Significant	-5	
Scar	Fully Mobile	+10	
	< 1/4 Adherent	-5	
	1/4 – 1/2 Adherent	-6	
	> 1/2 Adherent	-10	
Skin	Sensate	+6	
	Insensate	-6	
	Insufficient	-6	
Length	Suitable	+10	
	Acceptable	+5	
	Unsuitable	-10	
Shape	Conical/Cylindrical	+6	
	Bulbous	-6	
Tenderness	None	+10	
	Moderate	+5	
	Severe	-10	
Proximal Joint Contracture	None	+10	
	< 20°	+5	
	> 20°	-20	
Bone End Sculpted	Satisfactory	+10	
	Acceptable	+5	
	Unsatisfactory	-10	
	Bone End Exposed	-20	
Dog-ears	None	+6	
	Minimal	0	
	Significant	-6	
Redundant Tissue	None	+6	
	Minimal	+3	
	Significant	-6	
Additional Scars	No	+6	
	Yes	-6	
		Total	

of individuals undergoing major lower extremity amputations reported individuals who were able to walk before amputation had 14.4 times the odds of walking with a prosthesis post-amputation.[12] Such findings have likely influenced patient selection for prosthetic fitting. Indeed, it has been demonstrated that the ability to walk independently before amputation is a common determinant for receiving a prosthesis after amputation,[11,13] further lessening the potential for prosthetic ambulation in premorbid non-ambulators.

The presence of medical comorbidities in general have unclear influence on ambulation potential after lower extremity limb loss.[14] However, peripheral vascular disease specifically is likely a negative predictor for walking after amputation. Many studies have described poor outcomes, including reduced mobility, after amputation due to peripheral vascular disease.[15] A recent retrospective analysis of 42 patients with a history of dysvascular amputation concluded that an outpatient prosthetic training program was associated with improvements in performance-based functional measures including ambulation.[16] Despite these improvements, gait speed and performance remained notably inferior to clinically important thresholds, indicating that this population may have a reduced capacity for community-level ambulation and a higher risk for falls.[16]

The connection between age and outcome after amputation is complex. An association between advancing age and reduced ability to ambulate has been inferred.[15,17,18] Schoppen et al[18] evaluated 46 patients over the age of 60 undergoing unilateral amputation and demonstrated a consistent association between older age and reduced function. However, this finding is confounded by the interdependence of age, chronic disease, and pre-amputation fitness. As the incidence of medical comorbidities rises with age while fitness declines with age and chronic disease, it may be challenging to standardize for the influence of age alone.[19]

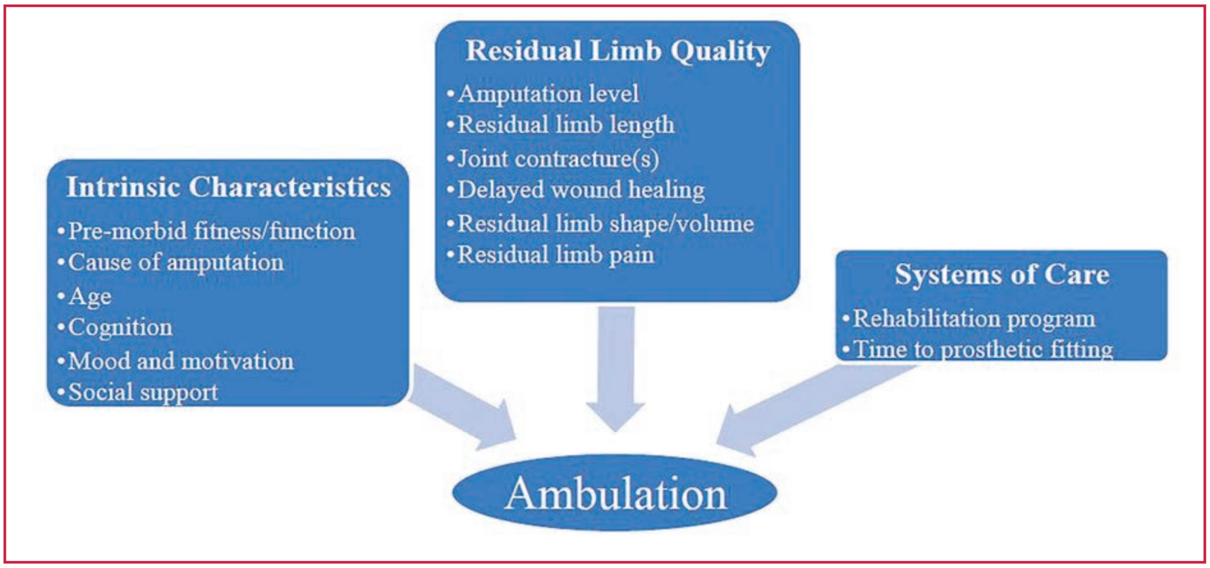

Figure 1. *Predictors of ambulation after lower extremity limb loss.*

A final intrinsic condition worth mentioning is the individual's mental state, including cognitive ability, mood, and motivation. Premorbid dementia has been associated with a lower probability of independent living and walking after amputation.[7,12,13,20] Larner et al[21] found that individual performance on a learning ability test was predictive of the capacity to learn to use a prosthesis after amputation. Meanwhile, reduced overall mental health status as well as lower attention and working memory scores have been linked to lower levels of prosthetic use and mobility 1 year after amputation.[22] It has also been suggested that mood disorders, particularly depression and anxiety,[23] as well as low patient motivation[24] are likely to negatively influence outcomes after lower extremity limb loss.

Residual Limb Qualities

Regarding the residual limb itself, the level of amputation is believed to play an important role in patient outcome. Energy expenditure during ambulation is expected to be greater with more proximal amputations. It has been estimated that individuals with transtibial amputations expend 9 to 33% more energy, and those with transfemoral amputations expend 37 to 100% more energy when walking compared to those without amputations.[25] This energy cost may limit ambulatory potential, particularly in individuals with lower premorbid fitness. In support of this, several studies have corroborated longer walking distances[15,26] and faster walking speeds[27] in transtibial compared to transfemoral amputees. Through-knee amputations generally demonstrate outcomes (eg, prosthetic use, walking distance, and walking speeds) that are inferior to transtibial amputees but superior to transfemoral amputees.[28-30]

It has also been suggested that bilateral amputees expend greater effort than unilateral amputees,[31] which is again expected to affect walking ability. Indeed, in a study comparing 15 bilateral and 15 unilateral (primarily transtibial) traumatic lower extremity amputee patients, bilateral amputees demonstrated decreased prosthetic use as well as reduced walking speeds.[32] A systematic review of 27 studies of military and civilian patients with traumatic lower limb amputations revealed that a higher proportion of below-knee and through-knee amputees were able to walk more than 500 meters when compared to above-knee and bilateral amputees.[33] Notably, there was no significant difference in mobility between the unilateral above-knee and bilateral amputation groups.[33] Similarly, Eskridge et al[34] surveyed 82 patients with lower extremity amputations and found that a higher proportion of individuals with unilateral below-knee amputations were able to easily perform various mobility and walking tasks, with fewer differences noted in the unilateral above-knee and bilateral amputation groups. Taking this a step further, the authors found that more unilateral below-knee amputees reported the ability to run one block when compared to unilateral above-knee and bilateral amputees.[34] Thus, it might be inferred that patients with more proximal unilateral amputations (eg, transfemoral and hip disarticulation) and bilateral lower extremity amputations generally have worse mobility outcomes.

Residual limb quality is another important determinant of walking ability after amputation. One marker of residual limb quality, residual limb length, is likely to influence energy expenditure and in turn walking tolerance, with longer residual limb lengths linked to lower energy requirements.[35] Pohjalainen et al[26] evaluated 155 consecutive patients with lower limb amputation and found that among those with transtibial amputations, a longer residual limb was associated with greater walking distance. A similar pattern was observed in the transfemoral amputation group, although not statistically significant.[26]

The shape, volume, flexibility, and position of the residual limb are also important determinants of prosthetic fit and, in turn, ambulation.[35-37] In particular, joint flexion contractures involving the hip (for transfemoral amputees) and/or knee (for transtibial amputees) can result in suboptimal limb position, altered biomechanics, and impaired gait. One study linked the presence of a hip flexion contracture to lower mobility scores in individuals undergoing bilateral transfemoral amputations,[36] whereas another study found that the absence of hip and knee contractures was a significant predictor of successful prosthetic ambulation in a mixed population of transfemoral and transtibial amputees.[38] Wound complications and delayed healing may also be problematic, resulting in postponed postoperative rehabilitation and prosthetic fitting.[19,35,38] Other negative prognosticators related to residual limb structure potentially include bulbous shape, poorly controlled edema, adherent scars, and redundant tissue.[35] A grading system to quantify residual limb quality has been proposed, which may help more accurately predict outcomes and mobility scores (Table 1).[39]

Lastly, the presence of pain involving the amputated limb has been consistently associated with impaired mobility.[15,26,36] Residual limb pain (formerly "stump pain") refers to pain involving the remaining limb after amputation. This can have many causes including, but not necessarily limited to, scar tissue, neuroma, insufficient tissue coverage, bone spurs, vascular insufficiency, and infection. In contrast, phantom limb pain describes the perceived sensation of pain involving the portion of the limb that has been amputated. It remains unclear whether a specific type of pain, residual limb versus phantom, may have a greater negative effect on walking ability, as most studies to date combine the two for analytic purposes.

Systems of Care

The rehabilitation process reflects an important component of recovery after lower extremity limb loss. A specialized rehabilitation program plays a vital role in upholding ambulatory capacity and community reintegration. Several large retrospective studies have demonstrated increased medical stability, improved 1-year survival, and a higher likelihood of prosthetic prescription among individuals exposed to inpatient rehabilitation.[40,41] Rau et al[42] compared a group of amputees undergoing an intensive training program comprised of strengthening, weightbearing, coordination, obstacle management, and functional exercise to a group undergoing a supervised walking program alone, and the authors found improved weight-bearing capacity and 2-minute walk test performance for those receiving rigorous physical therapy. Further investigation is necessary to establish the ideal setting and process for post-amputation rehabilitation.[23]

As an extension of specialist rehabilitation treatment, the provision of a prosthesis is necessary to optimize mobility. In general, earlier prosthetic fitting is favored. It has been suggested that overall satisfaction and utilization of a prosthesis is maximized when pretraining wait times are less than 60 days.[43] Conservatively, initial prosthetic fitting within 6 months may be appropriate to ensure wound healing and limb shaping, particularly in the context of dysvascular amputations.

Nonetheless, several interventions may help reduce time to prosthetic fitting. The use of a rigid dressing in the immediate postoperative period was recently shown to result in lesser times to fitting of a prosthesis.[44] It has also been suggested that the application of an immediate postoperative prosthesis or pneumatic post-amputation mobility device may result in shorter intervals to prosthetic fitting[45,46]; however, one contemporary study failed to associate an immediate postoperative prosthesis with earlier physical activity.[47]

Predictors of Running after Lower Extremity Amputation

Of patients who are able to achieve basic ambulatory skills, only a subset will attain the ability to run. In fact, one study found that that only 5% of previously active individuals reported running regularly after lower extremity amputation.[48] Respondents in this study indicated that jogging was among the activities that caused the most discomfort. In addition, running and jumping were the most physically difficult to perform.[48]

The transition of walking to running is marked by the elimination of a double stance phase of gait and is associated with higher vertical ground reaction forces. Muscle activity increases to respond to the higher demands of weight acceptance and to promote acceleration of the limb against the forces of gravity and the running surface. The amputee runner, however, must compensate for the loss of muscle absorption and propulsion ordinarily provided by way of the foot and ankle. To this end, the hip extensors become a major source of energy absorption and generation.[49] Amputee runners also demonstrate reduced mechanical work of the prosthetic limb during stance phase with a concurrent increase in mechanical work of the intact limb, resulting in energy transfer across the pelvis that is critical to uphold propulsion.[49,50]

It is not surprising then that hip strength, and particularly hip extensor strength, appears to be an important determinant of running capability after lower extremity limb loss. Hip and thigh weakness have been frequently reported in sedentary individuals after amputation.[51-53] More recently, Nolan et al[54] compared hip strength between sedentary amputees and sports-active amputees and found significantly greater peak hip flexor and hip extensor torques among active amputees. There was relatively little asymmetry in hip flexor and hip extensor strength between the residual and intact limbs of active amputees, whereas the inactive group demonstrated considerable relative weakness in the residual limb.[54] In particular, hip extensor peak torque of the residual limb in the active group was double that of the inactive group, and was up to 26% greater than that of an active, able-bodied comparison group.[54] Correspondingly, the application of a directed training program emphasizing hip strength and balance has been shown to promote running following limb loss.[55] Among eight individuals with a history of lower extremity amputation, six (three transtibial and three transfemoral) were able to run within 10 weeks of such a prescribed rehabilitation program.[55]

Dynamic balance is also likely to influence running ability after lower extremity amputation. Balance is impaired after amputation due to loss of proprioception as well as motor function from the foot and ankle mechanism and also the knee (for transfemoral amputees).[18,56] Single-leg balance on the intact limb has been implicated as a predictor of functional outcome in amputees.[18] One study found hip extensor strength followed by the ability to balance on the sound limb (without the use of the upper extremities) to be the two most significant contributors to walking speed during a 6-minute walk test.[57] Regarding higher-level mobility more specifically, Gaurnard et al[58] concluded that rehabilitation factors, and explicitly lower-limb strength and dynamic balance, were associated with greater high-level mobility.

With these predictive factors of strength and balance in mind, the Comprehensive High-Level Activity Mobility Predictor (CHAMP) was developed to quantify function and gauge readiness for higher levels of activity in individuals with lower extremity limb loss.[59] Specifically, CHAMP comprises four tests that measure coordination, power, speed, and agility (Table 2). Each test item is scored on a scale of 1 to 10 for a total of 40 possible points, with higher scores reflecting better performance.[60] For reference, one study reported an average CHAMP score of 35.4 (range, 33-39) for active, non-disabled individuals.[60] Higher CHAMP scores have been associated with higher amputee mobility predictor scores as well as enhanced performance on a 6-minute walk test, supporting CHAMP as a tool to help predict

Table 2. *The Comprehensive High-Level Activity Mobility Predictor*

CHAMP[1] Test Item	Skill(s) Measured	Testing Procedure
Single Limb Stance	Balance, Postural stability	Subject raises foot ≥15.2 cm from the floor, maintaining single limb stance. Number of seconds (up to 30) without error is recorded.
Edgren Side-Step Test	Coordination, Power, Speed and Agility	Subject performs side-step for 10 seconds. Number of one-meter intervals completed is recorded.
T-Test	Coordination, Power, Speed and Agility	Subject moves through a T-shaped course: forward, lateral (both left and right), and backward. Time to complete course, in seconds, is recorded.
Illinois Agility Test	Coordination, Power, Speed and Agility	Subject moves through a pre-set course that involves forward running and weaving. Time to complete course, in seconds, is recorded.

[1]CHAMP = The Comprehensive High-Level Activity Mobility Predictor

higher-level mobility in amputees.[60] It is worth noting that CHAMP has been validated specifically among male servicemembers with a history of traumatic lower extremity amputation. Further studies are needed to substantiate its use in more diverse populations of individuals with lower limb loss.

CONCLUSION

Many variables influence the ability to ambulate after lower extremity limb loss. Predictive factors for walking at a minimum include pre-amputation fitness, history of peripheral vascular disease, mental status, post-amputation pain, and residual limb quality, as well as referrals for specialized rehabilitation and early prosthetic fitting. Superior hip strength and dynamic balance further differentiate the capacity for advanced mobility, including running. It is especially important to direct interventions toward those modifiable factors in order to maximize ambulatory potential and foster physical activity after amputation. This may include psychological support, optimization of residual limb shape, pain control, earlier prosthetic fitting, and rehabilitation programs emphasizing lower limb range of motion, hip strength, and dynamic balance.

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