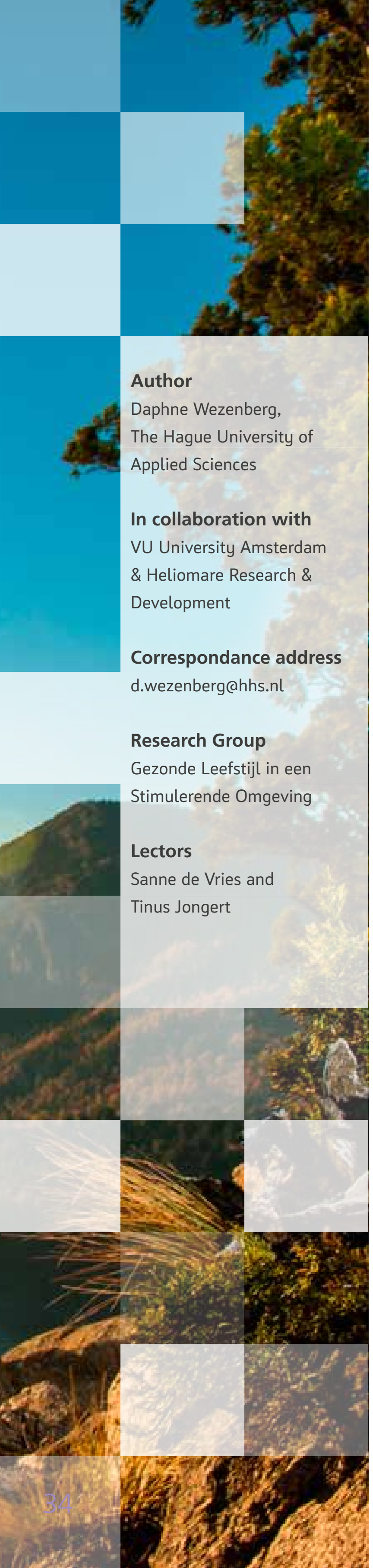
OPTIMIZING PROSTHETIC GAIT;

BALANCING CAPACITY AND LOAD



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Research Group
Gezonde Leefstijl in een
Stimulerende Omgeving

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Samenvatting

Het ondergaan van een eenzijdige beenamputatie is een drastische chirurgische ingreep. Mensen, die na een amputatie in staat zijn om te lopen met een prothese, zijn functioneel onafhankelijker, en hebben een hogere kwaliteit van leven dan mensen die in een rolstoel belanden. Het is daarom niet verrassend dat het herwinnen van de loopvaardigheid één van de voornaamste doelen is tijdens de revalidatie. Doel van het onderzoek was om inzicht te krijgen in de factoren die het herwinnen en onderhouden van de loopvaardigheid van mensen na een beenamputatie beïnvloeden. Gebaseerd op de resultaten van het onderzoek kan geconcludeerd worden dat de fysieke capaciteit hierbij een belangrijke rol speelt. Een relatief kleine verbetering in de capaciteit kan al resulteren in significante en klinisch relevante verbeteringen. Hoewel geavanceerde prothesen de mechanische belasting van het lopen met een beenprothese verminderen, kan een ineffectieve balanscontrole deze positieve resultaten weer tenietdoen.

OPTIMIZING PROSTHETIC GAIT;

Balancing capacity and load

Lower limb amputation – the surgical removal of a lower limb or part thereof – has been one of the first surgical procedures ever performed. Back then and still today, amputation is a life-changing surgery. The quality of life of those who have undergone an amputation greatly improves when they regain their ability to walk with the aid of a prosthesis. Unfortunately, walking with a prosthesis is not easy and people can face many challenges and problems.

Many people not familiar with the field of prosthetic rehabilitation, immediately think of a trauma as being the major cause for an amputation. However, in developed countries, the vast majority (87-94%) of lower limb amputations is performed due to vascular deficiency (Dillingham, Pezzin, & MacKenzie, 2002; Rommers, Vos, Groothoff, Schuiling, & Eisma, 1997); whereas a substantially smaller number of amputations are performed due to trauma (3-4.6%) (Dillingham, et al., 2002; Ephraim, Dillingham, Sector, Pezzin, & MacKenzie, 2003; Rommers, et al., 1997). An even smaller number of people undergo amputation due to a congenital limb deficiency (Ephraim, et al., 2003), or a malignant cancer (Ebskov, 1993). The most recent numbers collected between 2003 and 2004 in the North of Holland, show that incidence rates are 26.4 for people aged 45 and over (Fortington, et al., 2013). In the developed countries, incidence rates are expected to aggravate even further in the coming years as lifestyle-related diseases like peripheral vascular disease and diabetes mellitus become more common(Ziegler-Graham, MacKenzie, Ephraim, Travison, & Brookmeyer, 2008).

Not surprisingly, the presence of a lower limb amputation drastically affects the quality of life (Eiser, Darlington, Stride, & Grimer, 2001; Pell, Donnan, Fowkes, & Ruckley, 1993; Sinha & Van Den Heuvel, 2011). Fortunately in recent years, technological advancements in operating techniques, prosthetic developments, and post-operative care have paved the way for significant improvements in the functioning and the quality of life of these patients. These developments are mediated by scientific research, yielding a continuous growing body of knowledge on the biomechanical abnormalities and compensational strategies used by amputees (Czerniecki & Gitter, 1996). Despite these scientific and clinical developments, people with a lower limb amputation still can face many problems and challenges, especially when it comes to walking with the prosthesis. But it might be a challenge worth taking as the level of mobility is an important determinant for the quality of life(Pell, et al., 1993).

Walking requires a balance between capacity and load

Insight into factors associated with people's walking ability (e.g. age, sex and level of amputation) is pivotal for intervention management and determining the likelihood of successful ambulation after amputation. However, merely assessing correlations between these factors and walking ability does not provide information about the underlying mechanisms and hence does not reveal direct targets for intervention. In the studies performed, a bio-physical approach was adopted. This approach focused on the importance of maintaining a balance between the physical capacity and the physical load imposed while walking. The term capacity can encompass various aspects of human functioning and in our studies we have focused on the aerobic capacity. Aerobic capacity is the peak metabolic power that can be derived from the oxidative pathways and is defined as the peak amount of oxygen that can be utilized during exercise(Day, Rossiter, Coats, Skasick, & Whipp, 2003).

The term aerobic load indicates the amount of oxygen that is utilized while performing an activity, which in this case is walking. The notion that the aerobic load while walking with a prosthesis is substantially increased is a notion firmly entrenched and supported by numerous studies (Detrembleur, Vanmarsenille, De Cuyper, & Dierick, 2005; Genin, Bastien, Franck, Detrembleur, & Willems, 2008; Tesio, G.S., & Moller, 1991; Waters, Perry, Antonelli, & Hislop, 1976). The combination of a low capacity and high loads render walking with a prosthesis a formidable challenge. People may adapt to the higher strain by reducing their walking speed since this reduces the imposed load which would make walking less demanding. The imposed load, divided by the available capacity, provides us with a quantitative measure for this balance, namely the relative aerobic load. Valid information about the relative aerobic load is imperative as it provides a firm scientific ground on which the necessity and structure of training regimes can be based.

Based on previous literature and clinical expertise, it was expected that aerobic capacity is an important determinant that enables walking with a prosthesis easier. Moreover, the ability to walk can be influenced by both the mechanical properties of the prosthesis and the aerobic load necessary for the balance control. In the following paragraphs, the results of a number of studies that are performed on both the aerobic capacity and aerobic load are summarized.

The aerobic capacity is reduced

The aerobic capacity is subject to both the ability of the cardiovascular and respiratory system to supply oxygen to the muscles, as well as the ability of the skeletal muscles to utilize this oxygen. The magnitude of peak aerobic capacity is, aside from a genetic predisposition, dependent on person's activity level and sex, and is known to decline with age (Huggett, Connelly, & Overend, 2005). Most of the people undergoing lower limb amputation are older adults who have had long periods of pre-operative immobility, followed by a long period of convalescence due to, for example, delayed wound healing(Saw, et al., 2006). Hence, these people are likely to have a severely reduced aerobic capacity compared to their non-amputated healthy counterparts (Topp, Ditmyer, King, Doherty, & Hornyak, 2002). Remarkably though, only a limited number of scientific studies report on peak aerobic capacity in amputees, and even fewer have focused on the elderly amputee most at risk of a reduced aerobic capacity(van Velzen, et al., 2006).

The scarcity of articles reporting the measured aerobic capacity of people after lower limb amputation might be attributed to the problems encountered when performing a maximal exercise test in this specific patient group. The impaired motor system, reduced muscle mass, balance problems, localized problems in the stump as well as the contra-lateral limb, and the high prevalence of secondary coronary arterial diseases all make a standard graded exercise test unsuitable. To overcome these difficulties, a safe and valid method to test these patients was developed (Wezenberg, de Haan, van der Woude, & Houdijk, 2012). In total, 36 older amputees and 21 healthy controls performed a one-legged cycle exercise test. The exercise test proved to stress the cardio-vascular system to a sufficient extent in both groups. With regard to validity, it was determined that the one-legged exercise test had both a high construct and a high concurrent validity. This test was later used to determine the peak aerobic capacity and how this was related to the presence, level and cause of the amputation in people who had had a lower limb amputation. Results showed that people with an amputation had a 13.1% lower peak aerobic capacity than healthy controls. Differentiation between etiologies revealed that traumatic amputees did not differ from controls, whereas the vascular amputees had a 29.1% lower peak aerobic capacity. Interestingly, no association between peak aerobic capacity and the level of amputation was found. The results corroborated the limited existing evidence and the intuitive notion that the peak aerobic capacity is reduced in people with a vascular amputation (Wezenberg, de Haan, Faber, et al., 2012).

The lower peak aerobic capacity combined with the increased aerobic load while walking with a prosthesis can result in a high relative aerobic load. The relative aerobic load was investigated and the associated effects of level and cause of amputation were determined in the same group as described above. Based on the results, it was concluded that when walking at their preferred walking speed, older vascular amputees walked at a 44.6% higher relative aerobic load than healthy controls(Wezenberg, van der Woude, Faber, de Haan, & Houdijk, 2013). Traumatic amputees compensated for the increased aerobic load by reducing their preferred walking speed to such an extent that the relative aerobic load equaled that of able-bodied controls. They did this even though this negatively influenced the walking economy. A data-based model was constructed to determine the potential effect of an increased aerobic capacity on peoples' walking ability in terms of relative aerobic load, walking speed and walking economy. This model denotes that for example, in vascular amputees a relatively modest increase in peak aerobic capacity of 10% can result in a 9.1% reduction in relative aerobic load, a 17.3% improvement in walking speed and a 6.8% improvement in walking economy (Wezenberg, et al., 2013). These results denote that aerobic training must indeed be considered an essential component of prosthetic rehabilitation.

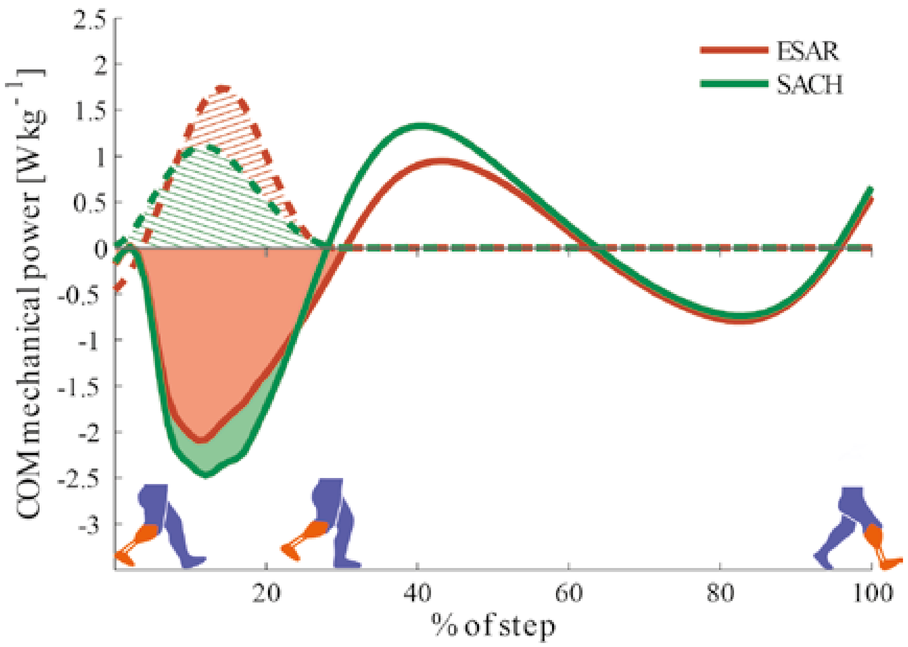
Aerobic load dependent on propulsion and balance

Aside from improvements in the aerobic capacity, efforts aimed at reducing the elevated aerobic load can improve the ability to ambulate as this reduces the relative aerobic load. However, the mechanisms responsible for the higher aerobic load in prosthetic gait are poorly understood. Two possible explanations have been proposed (Hoffman, Sheldahl, Buley, & Sandford, 1997). First, energetically costly biomechanical adaptations in the remaining joints are required to compensate for the absence of active ankle power during prosthetic push-off (Czerniecki & Gitter, 1996; Herr & Grabowski, 2012; Seroussi, Gitter, Czerniecki, & Weaver, 1996); and secondly, energy is needed for compensational muscular activity to ensure stability while walking with a prosthesis (Houdijk, Pollmann, Groenewold, Wiggerts, & Polomski, 2009; Segal, et al., 2011; Ventura, Klute, & Neptune, 2011).

Aerobic load for propulsion

To understand the importance of sufficient push-off power on the overall metabolic energy cost, human gait may be modeled as a double inverted pendulum. This so-called dynamic walking model was originally described by McGeer and colleagues (1990) (McGeer, 1990) and has been further elaborated upon by Kuo and colleagues (Kuo, 2007). According to this model, the overall metabolic energy cost while walking is closely related to the work performed during the step-to-step transition (Donelan, Shipman, Kram, & Kuo, 2004). Moreover, the cost for the step-to-step transition can partly explain the higher metabolic energy cost found in people walking with a lower limb prosthesis (Houdijk, et al., 2009). The most efficient way of reducing the step-to-step transition cost, and consequently reducing the metabolic energy cost, is by generating a push-off power along the trailing leg through ankle plantar flexion immediately preceding heel strike of the leading leg (Ruina, Bertram, & Srinivasan, 2005). In normal walking, this push-off power is primarily generated by the biological ankle muscles. In recent years, lower limb prosthetic developments have progressed exponentially and such prosthetic feet have been developed in order to improve the push-off power. One example of such a prosthesis is the widely prescribed energy storage and return prosthetic feet. These feet are able to store some of the energy normally dissipated at stance and return this energy during the push-off phase. To determine whether these prosthesis feet are able to improve the mechanical cost during the step-to-step transition, a total of 15 participants walked both with an energy storage and return (ESAR) prosthetic foot and a conventional solid ankle cushioned heel (SACH) prosthetic foot. The ESAR foot required the least mechanical work during the step-to-step transition (Figure 1).Unraveling of the causes for this reduction revealed that the improved push-off power and longer roll-over arc length of the ESAR prosthesis positively contributed to this reduction. A reduction in the step-to-step transition cost is assumed to be associated with a reduction in the overall metabolic cost required for walking (Donelan, Kram, & Kuo, 2002; Houdijk, et al., 2009; Segal, et al., 2011). Remarkably however, no convincing evidence is present in the literature supporting the notion that the metabolic energy cost is lower when walking with the ESAR foot (Hafner, Sanders, Czerniecki, & Fergason, 2002; Versluys, et al., 2009). The dynamic walking model proved able to differentiate between different prosthetic feet and this provides helpful and useful information about the center of mass work. However, it fails to fully explain the metabolic cost associated with prosthetic gait as improvements in step-to-step transition cost do not directly translate to corresponding reductions in the metabolic energy cost (Herr & Grabowski, 2012; Segal, et al., 2011). Apparently, other factors outside those related to step-to-step transition cost influence the overall metabolic energy cost.

Figure 1. Center of mass mechanical power profiles



The center of mass mechanical power profiles of the step during which the prosthetic limb is the trailing limb. Dashed lines represent center of mass mechanical power under the trailing limb, while solid lines represent the mechanical power under the leading limb. Hatched dashed and solid areas represent the part over which push-off work and collision loss was calculated, respectively.

Abbreviations: ESAR: energy storage and return foot (Vari-Flex, Össur, Iceland); SACH: soft ankle cushioned heel foot (1D10, Ottobock, Germany).

Aerobic load for balance

One of the possible factors influencing the overall metabolic energy cost while walking might be the energy required to ensure stability while walking (i.e. the ability to recover from and adapt to perturbations) (Lamoth, Ainsworth, Polomski, & Houdijk, 2010). The human ability to walk without falling, i.e. to remain in balance, depends on the interaction between the passive dynamics of the musculoskeletal system and the active control by the central nervous system. Human walking is, to some extent, passively stable in the direction of progression; however, it requires active balance control in lateral direction (Donelan, et al., 2004; Kuo, 1999). Gross control of lateral stability is predominately ensured by proper lateral foot placement (Kuo, 1999), while more refined adaptations are realized by lateral ankle movements after placement of the foot (Hof, van Bockel, Schoppen, & Postema, 2007).

Differentiating between the mechanical energy required for the walking movement and that associated with balance control is a challenge. In one study we tried to do this by having nine able-bodied healthy controls walk at an instrumented treadmill while following a projected step pattern composed of either their averaged step pattern (periodic trial), or a step pattern that was an exact copy, including variability of their unconstrained walking trial (variable trial). Results showed that walking an enforced gait pattern resulted in a metabolic oxygen increase of 8% in the periodic and 13% in the variable trial. It was postulated that the increased metabolic energy cost is related to increased preparatory muscle activation and a more active ankle strategy to control for lateral balance (Wezenberg, de Haan, van Bennekom, & Houdijk, 2011). It can be deduced that conscious placement of the feet in a designated position has a distinct metabolic energy cost.

To sum up, there is evidence that suggests that the aerobic load while walking with a prosthesis originates, in part, from the inefficient and inadequate push-off power resulting in an increased step-to-step transition cost and from possible alterations in the balance control strategy applied. While improvements in people's walking ability can be attained using state-of-the-art prostheses, improving people's walking ability to that of healthy controls involves more than developing a prosthetic ankle and knee that provides appropriate propulsion. Amongst other prerequisites, inefficient balance control strategy especially in challenging situations, can undo any positive effect of an improved propulsion power.

Walking ability explained?

The overarching aim of the described studies was to enhance our knowledge about some of the factors that influence the ability to regain and maintain walking after unilateral lower limb amputation. From the experiments conducted one can derive that having sufficient aerobic capacity could be a prerequisite in order to regain the ability to walk at a certain speed with a prosthesis. For example, vascular amputees are unable to walk at a walking speed similar to that of the able-bodied controls as this would require an aerobic effort that is beyond the aerobic capacity as measured during the one-legged cycling exercise test. Reducing walking speed is a method to ensure that the effort while walking (expressed as the relative aerobic load) does not surpass a predefined acceptable limit (Fiser, et al., 2010; Malatesta, et al., 2004). In addition to being a prerequisite that enables walking at a certain speed, it might be speculated that the relative aerobic load is an important factor governing the choice of walking speed. This speculation is based on the fact that people lower their walking speed even though it negatively affects walking economy (i.e. the slower walking speed requires more oxygen per distance walked) and prevents them from keeping up with able-bodied peers. Moreover, traumatic amputees reduced their walking speed to such an extent that it matches the relative aerobic load of the able-bodied controls (Wezenberg, et al., 2013). These results are interesting, as apparently the generally considered notion that walking speed is governed by walking economy is refuted for older people who walk with a lower limb prosthesis. However, these conclusions ought to be interpreted with care, as the association found between the relative aerobic load and the reduction in walking speed does not necessary imply causality. More importantly, relative aerobic load might be only one of the total sum of factors defining people's walking ability.

To recapitulate, people's walking ability is, amongst other factors, associated with the relative aerobic load. The higher the relative aerobic load while walking, the smaller the spectrum of functional walking speeds at which an individual with an amputation can comfortably walk. Moreover, understanding the (relative) aerobic load provides relevant information about the importance of adequate aerobic capacity, and therefore provides evidence that prosthetic rehabilitation ought to focus additionally on improving aerobic capacity. However, to determine causality, future studies should focus on the prospective association between relative aerobic load, aerobic capacity and the ability of people to walk with a prosthesis.

Improving aerobic capacity

In older subjects, the reduced muscle mass (J. L. Fleg & Lakatta, 1988) and mitochondrial capacity result in a reduced muscle oxidative capacity (Fiser, et al., 2010) and concomitantly, a reduced peak aerobic capacity (Jerome L. Fleg, et al., 2005). This reduction due to age is aggravated when combined with limited physical activity (Talbot, Metter, & Fleg, 2000). In the healthy elderly a reduced peak aerobic capacity limits walking ability (Fiser, et al., 2010), but in older people with an amputation this natural decline in peak aerobic capacity is superimposed on the already present capacity limitation due to behavioral characteristics (i.e. food intake, sedentary lifestyle or smoking) and pre-existing medical conditions(MacKenzie, et al., 2004).

Though the above clearly demonstrates the importance of an optimal aerobic capacity, several guidelines either do not mention aerobic training as a rehabilitation intervention(British Society of Rehabilitation Medicine, 2003; Broomhead, et al., 2006), or fail to provide specific guidelines for aerobic training (Nederlandse Vereniging van Revalidatieartsen, 2011; The Department of Veterans Affairs (VA) and The Department of Defense (DoD), 2007). Fortunately, some awareness of the importance of physical capacity exists as more than 80% of users and professionals in the field of prosthetics rate this aspect as an important predictor of prosthetic use. Despite the awareness, strikingly few longitudinal studies have been performed that investigate the effect of aerobic training on subjects' peak aerobic capacity and walking ability (Cumming, Barr, & Howe, 2006; van Velzen, et al., 2006). Those studies that have been performed involve traumatic amputees and report increases varying between 27.2% and 41.2% (Chin, et al., 2001; Chin, et al., 2002; Pitetti & Mancke, 2004). These results, together with the knowledge that aerobic exercise is beneficial in older adults with a wide range of pathologies (Mazzeo, et al., 1998), vindicates the notion that also in the vascular amputees improvements in peak aerobic capacity are possible.

To conclude, the reduced peak aerobic capacity and the high relative aerobic load together with the substantial improvement in walking ability that can potentially be attained by small improvements in peak aerobic capacity, underscores the importance of aerobic exercise training as an integrated part of prosthetic rehabilitation in the vascular amputees. Positive, though more moderate, effects are also expected for the traumatic population. The current lack of knowledge about effective training regimes and the concurrent effect on walking ability is at least remarkable, and future longitudinal studies targeted to improve the peak aerobic capacity are needed.

Future research directions

Prosthetic development and rehabilitation is an exciting research area which has become increasingly important due to the unfortunate growing numbers of people with a lower limb amputation. This article and the underlying thesis provides a starting point for a number of additional scientific studies that can contribute to the overarching aim to improve our knowledge of prosthetic gait. Currently, additional studies have been initiated that aim to improve our knowledge about how effective our current rehabilitation is with regards to improving the aerobic capacity. The outcome of this study combined with previous literature, provides evidence to further optimize rehabilitation.

Implications for rehabilitation

Based on the results from this thesis it is made eminent that in order to walk, subjects need to have sufficient aerobic exercise capacity. This is most pronounced in those patients who are de-conditioned due to a long period of inactivity, co-morbidity and/or a sedentary lifestyle. Therefore, rehabilitation ought to include some form of aerobic training aimed to improve the peak aerobic capacity in these patients. The one-legged exercise test that was developed and tested provides an excellent starting point that can be readily implemented in rehabilitation to gain insight in individual exercise limiting factors. Results obtained from this test enables development of efficient individualized training programs. The type of exercise ought to be chosen based on people's ability, preferences and should eliminate any risk factors (e.g. unwanted levels of cardiac stress). In addition to improving the physical capacity, health care professionals need to realize that balance control can influence a person's walking ability. Though further research is warranted, balance control might be trained using real-life situations during which (as in daily life) conscious control is directed away from the walking task. Another approach is to provide biofeedback through a mirror or computer screen. ■

(endnote)

This article is based on the work performed as part of my PhD which was completed in collaboration with VU University Amsterdam, Faculty of Human Movement Sciences and Heliomare Research & Development, Wijk aan Zee.

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Abstract

Undergoing a lower limb amputation is a life-changing surgery. The ability to walk greatly influences the subject's functional independence and quality of life. Not surprisingly, regaining walking ability is one of the primary goals during prosthetic rehabilitation. The primary aim of the research performed was to enhance our understanding of some of the factors that influence the ability to regain and maintain walking after a unilateral lower limb amputation. Based on the results we can deduce that a person's physical capacity plays an important role in their walking ability. Relatively small improvements in capacity could lead to significant and clinically relevant improvements in people's walking ability. Furthermore, results show that sophisticated prosthetic feet can reduce the mechanical load experienced when walking with a prosthesis. Interestingly, inefficient balance control strategies can undo any positive effect of these prostheses.