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ISSN: 2561-987X

PROFESSIONAL OPINION

Canadian Prosthetics & Orthotics Journal

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Editorial Office: cpoj@online-publication.com

ISSN 2561-987X

VOLUME 1, ISSUE 2

2 0 1 8

PROFESSIONAL OPINION

THE IMPORTANCE OF ADDITIONAL MID SWING TOE CLEARANCE FOR AMPUTEES

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ABSTRACT

Increased prosthetic hip to toe distance and insufficient mid swing toe clearance of a prosthetic foot is a well-recognized inadequacy for lower limb prosthesis users with wide and possible grave consequences on their ambulation capabilities. Most important are increased risk of falls and abnormal compensatory gait patterns with secondary unwanted physical effect like generally decreased mobility, muscular-skeletal pain and joint degeneration, i.e. osteoarthritis, with possible significant health economic effect. Even though insufficient toe clearance can be device related and technically or even intentionally induced for attaining equal length of the lower extremities in a neutral standing position or the stance phase, it is important to be aware of available technical solutions that can counteract the problem, like swing phase dorsiflexing feet, vacuum suspension systems, polycentric axis knees rather than single-axis knees and adequate knee flexion in early swing and swing-flexion assistance in the case of bionic knees.

CITATION

Lechler K, and Kristjansson K. The importance of additional mid swing toe clearance for amputees. Canadian Prosthetics & Orthotics Journal. Volume1, Issue2, No.1, 2018. DOI: <https://doi.org/10.33137/cpoj.v1i2.30813>

KEYWORDS

Prosthetics, Toe clearance, Lower limb prosthesis, Mobility, Prosthetic foot, Polycentric axis knees, Amputee.

INTRODUCTION

The shortest distance between the ground and the toe during level ground walking, referred to as the minimum toe clearance (MTC), occurs during mid swing phase (mid swing toe clearance: MSTC) and for abled bodies this averages to be around 15 mm.¹ This is the point in time during the gait phase where tripping is most likely to occur.²⁻⁴ Trip-related falls have been identified as the leading cause of falls for community-dwelling, middle-aged and older adults.⁵⁻⁷ Looking at elderly non-amputated women only, trips amount for up to 33% of the causes for their falling.⁸ Whereas women are more likely to fall while walking men are more likely to fall from loss of support by an external object rather than tripping, as well as falling while sitting down or rising from sitting.⁹ While most elderly amputees are men¹⁰ the risk of amputees in general to fall over a one-year period is 50% or higher.¹¹

Historically the first reported prosthetic leg offering additional toe clearance in swing dates back to 1805

(Fig. 1,2,3)¹², but still today most conventional prosthetic feet do not provide features for additional MSTC. This is despite the fact that historically various stumble preventing mechanisms for both trans-tibial and trans-femoral community ambulators have been offered since the early days of the industrial revolution, underlining the longstanding awareness of the importance of trips and stumbles as a cause for falls by amputees.¹²

WHY DO MANY PROSTHETICS SOLUTIONS NOT PROVIDE FOR MINIMUM TOE CLEARANCE?

The main reason for insufficient MSTC is the fact that conventional prosthetic feet do not dorsiflex during swing which places the MSTC on the prosthetic side below the MTC.¹³ Another well recognized reason is the vertical displacement between the socket and the residual during swing phase (pistoning) resulting in functional elongation of the prosthetic leg.¹⁴⁻¹⁶

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Disclosure: Full time employees of a medical device manufacturer, Össur ehf.

DOI: <https://doi.org/10.33137/cpoj.v1i2.30813>

Equal leg length in the stance phase yields an increased functional leg length in the swing phase of at least 16mm for a non-amputee.^{17,18} The functional prosthetic leg length with single axis knee is even further increased,¹⁸ resulting in a 22 mm lower MSTC compared to polycentric knees.¹⁹ In a 3D simulation with data from trans-femoral amputees' single-axis knees provided the least clearance (4.6 cm) during prosthetic swing phase, followed by four-bar knees (5.8 cm), and the two ankle mechanisms (6.4 and 8.7 cm).¹⁹

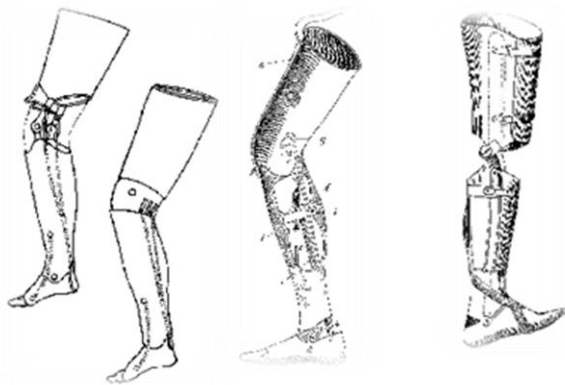


Figure 1. Anglesey TT and TF (1805) **Figure 2.** Erfurt TF (1880) **Figure 3.** Martin TT (1857)

BIOMECHANICAL AND PHYSICAL EFFECT OF INSUFFICIENT TOE CLEARANCE

For the purpose of overcoming amputees' experience of vertical displacement between socket and residual and the associated functional elongation of the prosthetic leg in swing phase¹⁴⁻¹⁶ the prosthesis is commonly aligned significantly shorter than the sound side. Amongst 113 trans-femoral and trans-tibial amputees 70 % were found to have a significant leg length discrepancy radiographically while balanced standing due to shorter alignment of the prosthesis compared to the sound side.²⁰ Gaunard et. al. showed that 66% of trans-femoral amputees had leg length discrepancies and for 57% the prosthetic side was shorter.²¹

Back pain is very common in lower limb amputees²² and has been linked to poor prosthetic fit and alignment, postural changes, leg-length discrepancy, amputation level, and general deconditioning.²³ The significance of this approach of leg length misalignment for the purpose of trying to make up for functional leg length increase during swing and the associated decrease in the MSTC is that leg length discrepancy can lead to various

health problems like back pain²⁴ and studies have shown it to contribute to back pain in amputees.^{25,26}

Not trying to adjust for the functional prosthetic leg length increase and to fit the prosthesis at an equal length to the sound side also carries with it a problem as pistoning in the socket and the changes in the trajectory of the prosthetic foot changes the point in time at which the physical maximum functional leg length occurs. For this additional functional swing phase leg length and time shift the amputees will try to compensate by developing their individual adaptation mechanisms. One is to elevate the contralateral side by early heel rise resulting in what is referred to as "Vaulting". Another is an arc-like movement of the prosthetic limb referred to as "Circumduction" and thirdly a lateral trunk inclination with definite raising of the hip on the prosthesis side. As a matter of fact, these three are the basic and main gait abnormalities characteristic for lower limb amputee in various degrees of combinations, even obvious to a lay observer.

Both stationary and functional leg length discrepancies cause abnormal forces on bones and joints likely to lead to degenerative conditions like osteoarthritis which has been found to be more prevalent in the contralateral limb than the residual limb of people with amputation.^{27,28} The increased prevalence of osteoarthritis is of concern, especially for people who have lived with an amputation for a longer time.²⁸ This actually turns out to be the case for many traumatic amputees who have been shown to have a significantly increased risk of suffering from osteoarthritis.²⁹

THE HEALTH ECONOMIC RELEVANCE OF TOE CLEARANCE

The proven relationship between insufficient toe clearance to trips and hence falls bring this feature into the scope of possible significant health economic effects. Although there is scarce published literature on the economic costs of falls within the amputee population, the costs of falls among older adults have been well studied. The estimated average one-year cost attributed to an elderly adult falling and requiring subsequent medical attention is between \$3,408 and \$4,872. Furthermore, if the fall results in a hospitalization, the cost may increase up to \$35,144 on average. Within this population, it is estimated that up to 1 in every 9 falls will lead to hospitalization.³⁰

A study on falls of amputees shows that up to 40% of their falls result in an injury and every other fall necessitates medical attention, which is higher than for the non-amputated elderly which has been estimated to be 30%.³¹ One study on trans-femorals indicated an estimated cost of \$25,652 at 6 months, for falls resulting in hospitalization, similar to the costs within the elderly.³² Direct medical costs of all falls in the USA was \$31.3 billion in 2015, up from \$30.3 billion in 2012.³³

Possible secondary health economic effect through back- and musculoskeletal pain and degenerative joint disease is also of real significance with osteoarthritis already accounting for 2% of years lived with disabilities.³⁴ OA is a rising concern specifically to amputees because they have a higher risk to suffer from hip and knee osteoarthritis.³⁵ Osteoarthritis often coexist with an amputation as pain does²⁸ and even further limits amputees in their mobility.³⁶ Osteoarthritis in the contralateral limb knee is 17 times higher than in age-matched non-amputees³⁵ and knee pain in unilateral amputees is twice as common.³⁵ Imaging studies have confirmed the increased prevalence of degenerative changes in the contralateral knee.^{37,38}

Since TTAs are known to load their intact limb to a greater extent than their prosthetic limb during gait,²³ the marked asymmetry in knee pain and degeneration suggests that mechanical loading factors are likely an important contributor to the increased incidence of OA. Not only asymmetries but also minor compensations can increase stress on the contralateral limb and possibly predispose the long-term prosthesis wearer to premature degenerative arthritis.³⁹⁻⁴⁰

REMEDIES FOR INSUFFICIENT TOE CLEARANCE

The most straight forward and natural action is the provision of prosthetic feet that dorsiflex in the swing phase and thereby compensating for the elongation in swing phase at the same time allowing for leg length equality in the stance phase or when standing.

Motorized and actively dorsiflexing prosthetic ankles have shown to significantly increase MSTC⁴¹ by about 70% and increase in MSTC of 25.6 ± 5.4 mm has been shown to lead to a reduction in falls⁴² over a one-year period for community dwelling amputees. Hydraulic ankles with dorsiflexion in swing have also been shown to increase the MSTC.⁴³

A recent study has shown in addition to increased MSTC during level ground walking that this can also be provided for during incline and decline walking (Figure 4).⁴⁴ An anecdotal user report from this same trial states: "My work environment involves walking through sloped tunnels and up/down stairs. I usually trip 1-3 times per day with my prescribed foot, but I never tripped with the Proprio-Foot!". Several studies had previously looked at and compared the MSTC of conventional ESAR feet versus dorsiflexing ankles (Table 1).

Table 1: Comparison of prosthetic side toe clearances in mm.

	Toe Clearance on the Prosthetic Side		
	Level (mm)	Slope (mm)	Decline (mm)
Fallers, Rosenblatt 2017	12.3		
Non-Fallers, Rosenblatt 2017	25.6		
Hydraulic, Johnson 2014	20.7		
Motorized, Fradet 2010		16.0	12.0
Motorized, Rosenblatt 2014	33.6		
Motorized, Lamers 2018*	14.6*	18.4*	11.7*

* compared and in addition to sound side

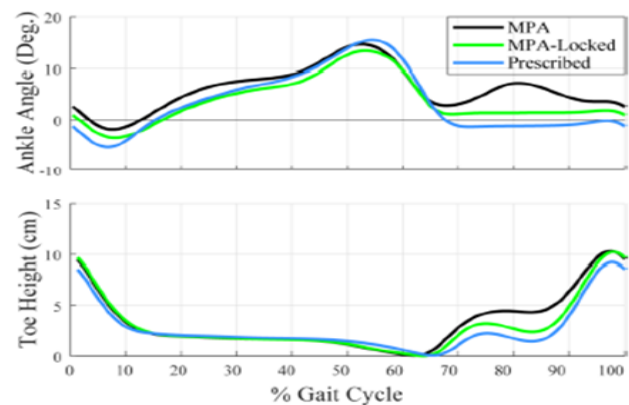


Figure 4. MTC with MPA(Proprio), MPA-Locked and conventional ESAR in level ground.⁴⁴

Other technical solutions that can improve the MSTC are vacuum suspension systems for reduced pistoning and functional swing phase prosthetic leg length increase. A study by Rosenblatt where falling rate and pattern was tracked over a one-year period for 27 amputees (15 vacuum assisted socket suspension (VASS) users, 12 non-VASS users) showed 75% less risk of VASS trans-tibial amputee users having multiple falls compared to non-VASS users.

Even though less effective than providing dorsiflexion ankles, selecting polycentric knees over single axis knees also helps with the toe clearance as previously outlined.¹⁹ Also providing a bionic knee like the Rheo Knee that has a rapid foot off velocity results in a higher MSTC compared to single axis knees.⁴⁵ Additionally, the rapid toe off velocity and lower hip torque qualities of the Rheo Knee results in earlier toe off at a slower than preferred walking speed and significantly less vaulting of the intact ankle, compared to for example a hydraulic knee ($P = 0,028$).⁴⁶

SUMMARY

Providing sufficient toe clearance on the prosthetic side allows aligning the prosthesis more equally and favorable influence in short term on low back pain and in longer term on side effects like lumbar scoliosis and osteoarthritis. Most importantly added toe clearance should result in fewer trips and stumbles resulting in decrease in falls. All of this can possibly result in significantly less health economic burden. A large study on patients having undergone hip arthroplasty ($n=753$) shows that leg length discrepancy reduces satisfaction and functional outcome after hip arthroplasty.⁴⁷ Reducing risks of falls reduces the degree of disability of amputees by improving their mobility and hence improves their quality of life.⁴⁸

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