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Biomechanics of Lower Limb Prostheses

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Abstract

Frequent lower limb amputations caused by the growing incidence of vascular diseases and traumatic injuries currently represent a significant global problem. A properly constructed and adjusted prosthetic device is a key to the reintegration of these patients into their family, social, and working environments.
The main objective of the submitted article is to provide a clear summary of the principles regarding the lower limb prosthesis construction, highlight the fundamental principles and rules to be applied to the assembly in the assembly stand, and the static and dynamic assessment of a prosthesis. The article also briefly points out the necessity of proper construction of a prosthetic socket and in the concluding part it describes unfavourable consequences of the failure to adhere to the structural lines and improper adjustment of components during the gait.

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*Keywords:*prosthesis; alignment; lower limb; biomechanics; gait

1. Introduction

Lower limb prosthetics are devices designed to replace the function or appearance of the missing lower limb as much as possible. The basic categories of lower limb prostheses are, by the amputation height, transtibial (TT) and transfemoral (TF) prostheses. Typical transtibial prosthesis consists of a prosthetic foot, tube adaptor, and transtibial socket; a transfemoral prosthesis consists of a prosthetic foot, tube adaptor, prosthetic knee joint, and transfemoral socket [1].

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Lower limb prostheses can be exoskeletal (prosthesis with the peripheral weight-bearing capacity, the use of which facilitates the transfer of a patient's weight to the ground along the device's circumference) or currently most frequently used endoskeletal – modular (prosthesis with the central weight-bearing capacity, the use of which facilitates the transfer of a patient's weight to the ground a tubular structure in the prosthesis centre) [3].

Health condition assessment and assignment to a functional regime is carried out considering the following aspects:

1. assessment of cardiovascular apparatus efficiency, especially in terms of load tolerance,
2. muscular power of a person insured, muscle tone, and locomotor finding,
3. self-sufficiency when applying an orthopaedic prosthetic device,
4. mobility of a person insured with an orthopaedic prosthetic device,
5. local finding on a residual limb and a residual limb's bearing capacity,
6. psychological preconditions for the use of prosthesis [2].

Upon the consideration of the above mentioned criteria, a physician proposes a patient to be assigned one of the following functional regimens:

1. I. extremely limited regimen, when a person insured requires the use of wheelchair for the disabled, using it alone or with the assistance of other persons; the user is able to stand up with a prosthesis, but cannot walk without another person's assistance, with a solid support they can only move from a wheelchair to a different place (to a bed, chair, bathroom)
2. II. limited regimen in the interior, when a person insured moves indoors. They are able to manage an alternate regimen, they move using a wheelchair and crutches, or with the aid of a solid support (hand rail, table and wall) for shorter distances, they are able to stand up and sit down without assistance. They can walk approximately 30 to 50 meters.
3. III. common regimen in the interior, when a person insured moves indoors. They use a wheelchair only exceptionally, they are able to move to a different place without a support or using crutches or a stick, they are able to walk through small obstacles (door sills, carpets) and up the stairs with a rigid support. They can walk approximately 50 to 100 meters.
4. IV. common regimen in the exterior, when a person insured is able to walk outdoors. They almost never use a wheelchair, they are able to move to a different place using crutches or a stick and they walk through small obstacles (pavements, small stones, slightly inclined surface) and up the stairs using a support. They can usually walk 100-200 meters.
5. V. intensive regimen in the exterior, when a person insured manages more demanding movements in the exterior. They do not use a wheelchair, they manage movements without a support, rarely with crutches or a stick, they manage walking through various obstacles (pavements, small stones, walking on infirm terrain and inclined surface) and up the stairs without a support. They manage getting on and off the means of transport. They can usually walk several hundreds of meters; they manage a short run without a prosthesis using two Lofstrand crutches [8].

2. Biomechanics of physiological gait

Walking is the fundamental and the most important phenomenon in space and time, reflecting locomotor characteristics of an individual. It is characteristic with orthogonal body control, concurrent bending of the body, head, and upper limbs, and the method of using lower limbs. Human gait is carried out using the strategy called the double pendulum (Fig. 1). From the statokinetic point of view, it is a translational body movement in which the lever-rotary movement of lower limb segments is transferred into a rolling movement on pelvic joints. In the forward movement, a leg leaving the ground moves forward from the hip. This curve is a first pendulum; subsequently the heel touches the ground and rolls away towards a toe in a motion described as the inverted pendulum [9].

A conceptual diagram summarizes the dynamic walking perspective. The walker's center of motion (COM) follows a ballistic, passive trajectory during the single-support phase governed by the dynamics of an inverted pendulum. During the double-support phase, or step-to-step transition, the positive work of the trailing leg and the negative work of the leading leg (upward pointing arrows) redirect the COM's trajectory from a downward arc to the upward arc necessary for the next step. The energetic cost of this redirection of the COM is proportional to α.

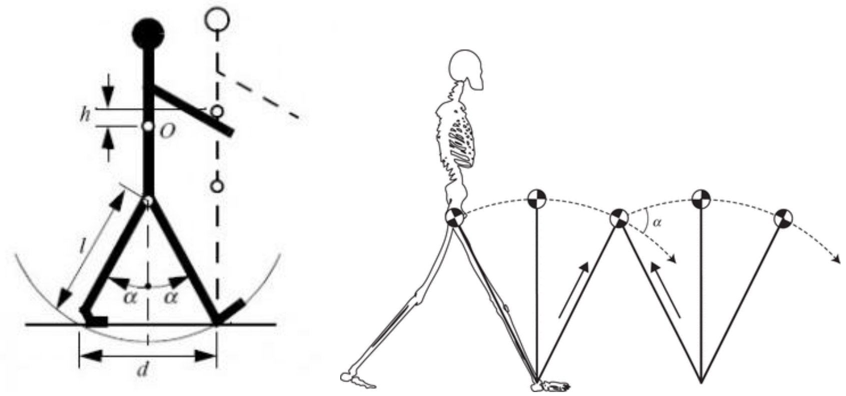

Fig. 1 Double Pendulum Strategy. d – step length, l – pendulum arm, h – the shortest distance of the gravity centre during the movement in the vertical direction, α – angular acceleration.

A gait cycle is a period beginning with the initial contact between the heel and the ground of one leg up to the subsequent contact between the heel and the ground of the same leg (Fig. 2). A basic unit of the human gait is a step which is divided into 2 basic phases: the support phase and the swing phase.

In the support phase, a foot touches the ground and it takes approximately 60% of the overall cycle duration. The support phase can be double (in the beginning and in the end of the cycle), when the support is provided by both limbs, and a single, when only one limb touches the ground. In the double support, both limbs touch the ground. The main task of the support limb is to transfer the pelvis and the upper body part from the back position to the front position in the lowest arch, so that the support limb intercepts a body fall in time (i.e. protects the centre of gravity from lowering too low) and spring-back the impact, following the activation of respective muscles (quadriceps and dorsal flexors). After the foot steps onto the ground, the body weight impact evokes the reaction that transfers it into the propulsive push-off force. The push-off begins with the plantar flexion of the ankle, by which the heel rolls away from the ground (triple-headed muscle of calf and plantar muscles). By the activation of the retromalleolar muscles, the ankle lifts angle-wise upward and forward and finally the long flexors of the big toe and toes are activated and they complete the push-off. The push-off is completed when a foot leaves the ground [7].

The swing phase begins in the end of the support phase, immediately after the push-off, and takes 40% of the gait cycle. In the swing, knee flexors are initially activated, they adduct the lower leg onto the ground. The balance of the swinging limb is thus disturbed which causes the swing of the entire lower limb forward. By the inertia force, the lower limb gets beyond the vertical axis, where m. iliopsoas is activated and it pulls it to the required flexion in the hip joint. In this phase of the swing, the knee flexors lower the lower leg down to the ground and finally release it completely, which causes it to swing. By active movement of the thigh, the lower leg is transferred beyond the vertical axis to extension, to which it is completely adducted by quadriceps [4].

Table 1 Gait cycle

GAIT CYCLE	
Support phase	
Initial contact (0%)	Initial contact, when the heel touches the ground, hip joint is in flexion, knee is in extension. The ankle is transferred from the dorsal flexion to a neutral position. The opposite leg is completing the support phase. The most activated muscles are m. gluteus maximus, medius and m. peronaeus.
Loading response (0-10%)	Double support phase. The foot touches the ground and continues, until the second foot is elevated

	for a step. The entire body weight is transferred to the support leg. The role of this phase is initially the shock absorption, body weight transfer, and forward movement. Concurrently, the entire support is ensured by one leg that must provide stability to the body. In this phase, quadriceps femoris and m. tibialis anterior are activated. In this phase, the knee is not extended.
Midstance (10-30%)	It begins with the elevation of the opposite limb and continues, until the entire body weight is transferred to the support limb. The hip and the knee of the support limb are in extension. The leg is in the dorsal flexion. Posterior calf muscles are primarily activated.
Terminal stance (30-50%)	Heel of the support limb starts to roll away from the ground, until the heel of the opposite foot touches the ground. Extension of the support leg in the hip joint increases and thus the body weight is transferred forward beyond the vertical axis of the body.
Preparation for a step (50-60%)	It is the second double support phase. This phase ends by the toe rolling away from the ground. After the opposite foot touches the ground, the plantar flexion of the ankle and knee increases and the hip extension decreases. Lower limb transfers the body weight on the opposite leg which becomes the support limb. Reduction of the extension in the hip and increase in the knee flexion is facilitated by the activation of m. sartorius, m. rectus femoris and m. psoas major/ minor and m. iliacus. Toe takeoff from the ground is ensured by the m. flexor halucis longus.
Swing phase	
Initial swing (60-70%)	It begins with the elevation of feet from the ground and ends when the swing limb is opposite the support limb. The flexion in the hip and in the knee increases and the ankle is in the partial dorsal flexion. The flexion is most visible in this phase. The opposite limb is in the centre of the support.
Mid-swing (70-85%)	Continuation of the step until the phase when the swing limb is in front of the body and fibula is in the vertical position. The hip is flexed; the knee can perform the extension in reaction to the gravitation force. It continues from the dorsal flexion to the neutral position.
Step termination (85-100%)	It begins when the fibula is in the vertical position and it ends when the foot touches the ground. The knee is extended by m. quadriceps femoris and the flexion in the hip is facilitated by lateral group of adductors. The ankle remains in the transition from the dorsal flexion to the neutral position.

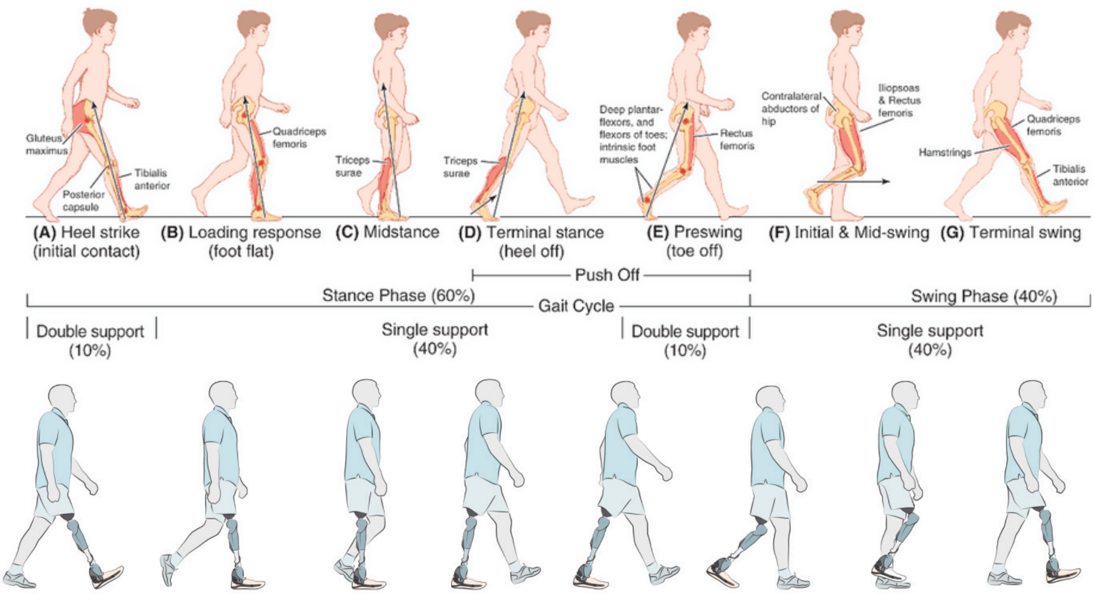

Fig. 2 Normal gait cycle vs. gait cycle with prosthesis

3. Construction of prostheses

In majority of individuals with both limbs, the weight is distributed in the 50:50 ratio which facilitates ideal symmetric loading of lower limb joints. In such distribution, energy consumption is not increased to maintain the balance and there no unnecessary compensation movements must be made in the area of ankle and foot. With amputations, the load is often transferred through the tuberosity of the ischium which is unsuitable due to changed position of the centre of gravity in the frontal plane; the centre of gravity is moved laterally to the healthy limb side. By proper construction and a suitable selection of components it can be arranged that the TF prosthesis transfers at least 40% of the individual's body weight.

Stabilizing activity of the limb/prosthesis depends on the amputation height, i.e. on residual muscles that remained on the residual limb. In the amputation intervention, the muscles are transacted in various heights, depending on the damage, and thus the muscular function is reduced (flexors/extensors, abductors/adductors).

Important factors for the creation of properly functioning prosthesis include:

1. Selection of appropriate components that depends primarily on the physical and mental condition of the user, user's activity, and method of use. The principal factors for the selection of prosthetic components are a patient's weight and physical activity. Depending on the user's weight, the material of prosthetic parts is selected so that sufficient strength and average weight of transtibial prosthesis is ensured.
2. Residual limb's conditions, amputation height, residual limb's shape (conic – smaller circumference on the distal part than on the proximal part, pear-shaped, cylindrical – the same circumference on the distal and proximal end), amputation scar, as well as other problems or diseases
3. Construction of prosthesis that can be divided into following steps: basic construction, static and dynamic correction [6].

The load line is important for the proper distribution of the user's body weight (Fig. 3). For the proper construction of the prosthesis, it is important to identify the course of this line. It is a thought vertical line which in a healthy individual runs in the sagittal plane through the centre of gravity, then 2mm posterior from the hip joint, 15mm anterior from the knee joint, and 60mm anterior from the ankle joint (Fig. 3). In the frontal plane, the load line runs through the centre of the body; when the prosthesis is constructed, it should run through the centres of above mentioned joints of one limb. In such case it is a stabile stance when the foot should be able to compensate the horizontal movements of the centre of gravity by shifting the weight forward or backward, to the left and to the right side [8].

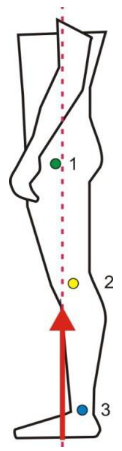

Fig. 3 Load line: 1. - 2mm posterior from the hip joint, 2. - 15mm anterior from the knee joint and 3. - 60mm anterior from the ankle joint.

Construction of the prosthesis is the empirical process that depends on the skills of an orthopaedic technician and on a patient's feedback. The main objectives of the good construction of the lower limb prosthesis is to provide and ensure for the user sufficient certainty, stability, balance, and comfort during the stance and during the walk to minimize the energy cost and gait asymmetry. In the first phase, it is crucial to determine the construction line (Fig. 4), which is an arbitrary vertical line towards which individual prosthesis components are positioned according to certain rules (Table 2).

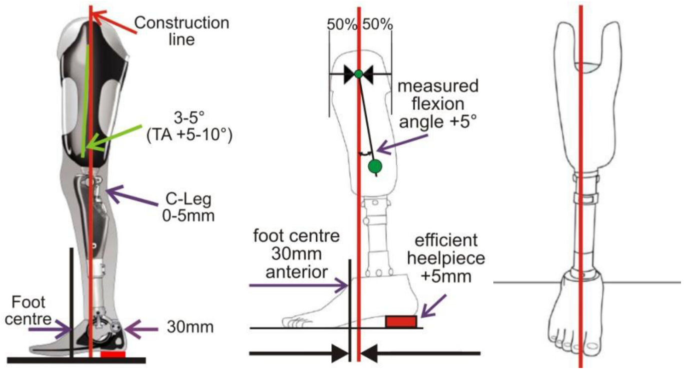

Fig. 4 Construction line

Table 2 Positioning of components according to certain rules

Construction			TT	TF
Basic construction	foot	Sagittal plane (AP)	Heelpiece height – efficient heelpiece +5mm Foot centre moved forward before the construction line in 30mm	
		Transverse plane	External rotation 5-7°	
	socket	Sagittal plane (AP)	Flexion – measured value of the flexion angle +5°	Flexion – measured value of the flexion angle +5° to 10°
		Frontal plane		Adduction angle, depending on the residual limb length 3, 7, 12°
	knee joint	Sagittal plane (AP)	-	Position according to the construction Rotation centre 20mm above the MPT of the second limb
Static correction	Frontal plane		Prosthesis length M-L foot position Pronation/supination	Prosthesis length M-L knee and foot position Pronation/supination
	Sagittal plane (AP)		Plantar flexion A-P foot position	Plantar flexion A-P knee and foot position
	Transverse plane		Foot shift	Foot shift
Dynamic correction	Frontal plane		Knee joint movement control in the support phase, minimum M-L forces	
	Sagittal plane (AP)		Knee joint movement control in the support phase, natural flexion and extension when loaded	
	Gait test in various environments			

The second step is the static adjustment of the prosthesis that is carried out together with the patient. By turning and shifting the components, required adjustments to the prosthesis construction are made, until the stability is achieved in the stance. In the static adjustment, it is important to adjust the correct prosthesis length so that both limbs are evenly loaded and the pelvis is leveled. Negative effect on the stance with a prosthesis is influenced by the shift of the load line caused by the plantar flexion of the foot or moving the foot forward.

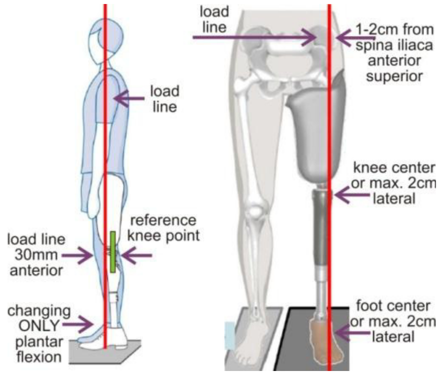

Fig. 5 Load line in TF

Other changes in the adjustment are carried out during the dynamic adjustment of the prosthesis when a patient's gait is assessed in the sagittal and frontal planes, deviations from the normal step cycle are examined. The deviations can be caused by improper construction of the prosthesis or by physical deficiencies, as well as a patient's mental condition.

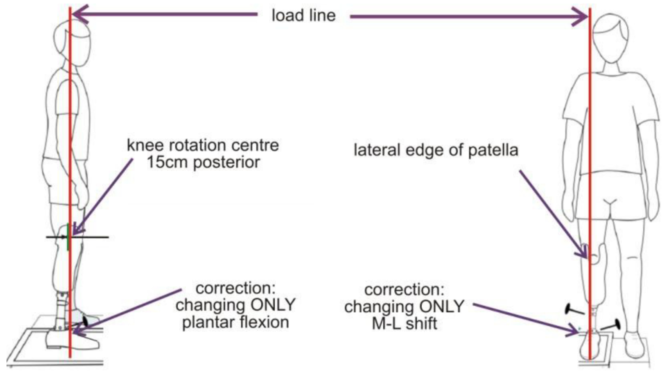

Fig. 6 Load line in TT

During the gait with a prosthesis, the first contact of the foot and the ground is important, as well as transfer of load on the foot. The foot contact is carried out through the heel so that the walking is as natural as possible, and subsequently the entire sole surface contacts the ground and the load is transferred to the foot. It is followed by the foot rolling away from the ground and the push-off through the toe, when the energy is required for the swing phase. In this phase, the important role is played by the proper selection of a foot (foot roll away from the ground, adaptation to the surface, compensation movements, energy accumulation and expenditure) and a proper position of the knee joint. Particularly these components and their proper assembly affect the final function of the prosthesis and thus influence the user's activity. In the swing phase, the knee function is important, as it is necessary to ensure the movement from flexion to extension (extension moment of the knee) which facilitates the foot transition from plantar flexion to dorsal flexion, i.e. the toe elevation, in order to avoid stumbling and subsequent fall of the user [1].

4. Biomechanics of the socket

The residual limb is placed in the socket that provides rigid and stable attachment to the limb, which is important for the control thereof. The prosthesis socket (Fig. 7) can be divided into 3 parts that have different functions. The top part is the so-called seating face, the central part is actually the controlling socket area with the function to ensure correct movement and restrain it in the P-A direction, which is important during the gait. The last part is the distal socket end which, in an ideal case, should transfer only 10% of an individual's weight to avoid inappropriate load transfer and subsequent damage to soft tissues.

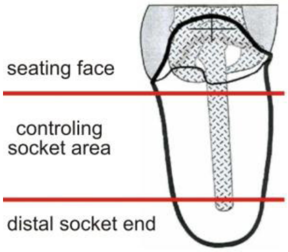

Fig. 7 Socket divisions

A socket must be able to transfer the load, ensure stability, and provide efficient control during the mobility. In a standing position, the m. gluteus medius is stretched; it ensures that the pelvis is maintained in a balanced position. In a healthy individual, this process is ensured by attaching the femur to the ground by a lower limb; in case of the lower limb amputation, this function is taken over by the prosthetic socket. Therefore, proper socket shape is important, as well as its ML and AP dimensions, so that the femur can be attached. In a transverse oval socket of transfemoral prostheses, the pressure on the distal femur end increases and the body is excessively bending aside to reduce the pressure (Fig. 8 left, middle). It is a non-physiological load transfer, as the load is transferred through the tuberosity of the ischium, which reduces the arm of the exerted force and the overturning moments are increased (Fig. 8 right). On the contrary, the longitudinal oval socket facilitates the physiological transfer, as the rotation centre is in the hip joint and the pelvis does not turn over (the pelvis is in a balanced position) and no unnatural stabilisation body movements are required [5].

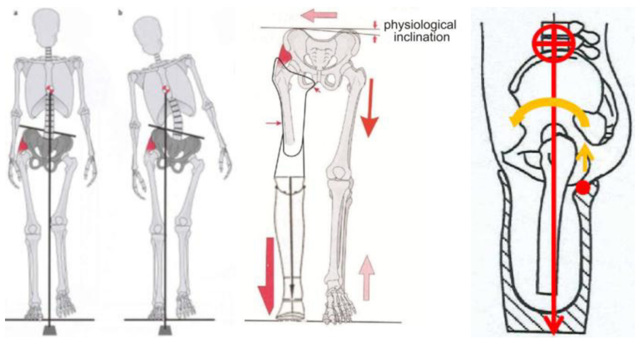

Fig. 8 Excessive body turnover to one side and torsion moment development

5. Gait deviation

If the prosthesis construction procedure and principles are not thoroughly complied with and a prosthesis is not properly aligned, undesired deviations from the physiological gait develop during walking. These deviations result in the increased energy cost during the motion, overloading of certain groups of muscles, and can cause damage to joint structures and skin. Another aspect is the gait aesthetic discomfort (step cycle asymmetry, body inclination, etc.) [6].

Most frequent demonstrations of improper construction of transtibial and transfemoral prostheses include:

1. Vaulting
   - amputee "steps up" to the prosthesis in order to complete the stride,
   - causes - prosthesis is too long or excessive knee unit resistance.
2. Medial / Lateral Whip
   - the heel of the prosthesis tracks closer / farther to the midline of the body at toe off,
   - causes - knee axis of the prosthesis is in excessive external / internal rotation or the prosthesis is donned in external / internal rotation.
3. Circumduction
   - the foot swings outward in an exaggerated arc during swing phase,
   - causes - prosthetic knee flexion resistance is too great for the patient, prosthetic knee flexion is limited for some reason, avoidance mechanism developed when the medial brim of the socket causes pain or length of the prosthesis is excessively long.
4. Lateral Trunk Bending
   - the patient has a leaning gait and the shoulder usually dips toward the affected side,
   - causes - the prosthetic foot is outset greater than 25 mm, incorrect prosthesis length, insufficient socket adduction or amputee sensitivity.
5. Excessive Heel Rise
   - the heel of the prosthetic foot comes up too far and too quickly,
   - causes - prosthetic knee flexion resistance is inadequate for the patient.
6. Drop Off
   - during late stance, there is sudden and excessive knee flexion,
   - causes - the keel of the prosthetic foot is too soft, the toe lever of the prosthetic foot is too short, or the heel height of the shoe is too high for the prosthetic foot being used.
7. Foot Slap
   - there is a rapid and uncosmetic plantarflexion movement immediately after heel contact,
   - causes - insufficient plantarflexion resistance in the prosthetic foot or excessively soft bumper in a foot with an articulated ankle.
8. Hyperextension of the knee on the affected side
   - the knee on the side with the amputation goes into hyperextension during the midstance (most visible just prior to heel off in the sagittal plane),
   - causes - potentially occurs when transferring an individual from a joint and thigh lacer prosthetic design to a patella tendor bearing design, a heel cushion that is too soft, a keel or toe lever arm that is too long or too firm (relative to the weight and activity level of the individual) or laxity of the posterior capsule of the knee or hamstrings tendons.
9. Pistoning
   - the individual's residual limb moves vertically during the alternate weight bearing and non-weight bearing periods during gait,
   - causes - the socket is too large for the individual or the suspension is inadequate.

Proper adjustment of the prosthesis is affected by a natural patient‘s walking stereotypes, function of the prosthetic foot and pressure on the stump, has a significant impact on comfort and energy consumption in the use of the prosthesis. Wrong prosthetic fitting can cause pain to users during the execution of daily activities. Manifestation of pain can correspond to lateral asymmetry of the body caused by incorrect length of the prosthesis or incorrectly selected components. Wrong construction of the prosthesis can lead to an imbalance of forces, overload muscle groups, risk of tripping and also to damage of soft tissues integration on the stump.

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