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Review article

Amputation and prosthesis fitting in paediatric patients

J. Griffet[a,b,c,*]

[a] Orthopédie pédiatrique, hôpital Couple-Enfant, CS 10217, 38043 Grenoble cedex 09, France
[b] Université Grenoble-Alpes, Grenoble, France
[c] Unité clinique de l'analyse du mouvement, institut Rossetti, Nice, France

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ABSTRACT

Amputation of a limb is always perceived as a catastrophe. The principles underlying creation of a stump adapted to modern prosthetic fittings must be fully understood and the patient managed by a multidisciplinary team. In paediatric patients, preserving residual limb length is a crucial point that should be assessed according to the expected growth potential. Advances in prosthetic fittings have led to changes in the overall concept of socket design, which seeks to achieve three objectives: to maximise the weight-bearing surface area, to eliminate friction of the skin on the socket, and to eliminate lever-arm effects. The introduction on the market of new materials has contributed substantially to advances in prosthetic fittings. These advances require the use of new criteria for stump quality and optimisation, which exert a considerable influence on prosthesis function. Prosthetic fitting and specific management of psychological and social problems are provided during an inpatient stay in a physical medicine department, by a team of physicians, other healthcare professionals, social workers, and educators. Three-dimensional imaging and gait analysis provide valuable information.

1. Introduction

Amputation of a limb during childhood is a rare event that is consistently perceived as a catastrophe, first by the family and later on by the child. The principles required to create a stump capable of accepting a function-restoring prosthesis must therefore be fully understood. The patient must be managed by a multidisciplinary team of professionals who work closely together. Although the paediatric orthopaedic surgeon is the first to intervene, an essential step – ideally taken before the amputation – is an in-depth discussion with a highly skilled orthopaedic prosthetist and with the staff of the physical and rehabilitation medicine (PRM) department who will be in charge of the patient during the adaptation phase. Multidisciplinary teamwork is required for stump wound care, selecting and fitting the prosthesis, and providing social support. Later on, the orthopaedic surgeon and other members of the multidisciplinary team must work together to monitor the patient's morphostatic development and growth, as well as to make decisions about changing the prosthesis. Unfortunately, amputation is often required as an emergency procedure. Therefore, every surgeon should know how to fashion a serviceable stump.

Considerable advances have been made in the field of limb prostheses. New materials have been introduced and new prosthetic designs created to improve performance. These changes mandate a reappraisal of the principles underlying amputation surgery. The review presented herein is based on recent technical progress in prosthesis development and on its implications for selecting the surgical technique and providing PRM management, with the assistance of new tools such as three-dimensional lower-limb imaging (EOS®) and quantitative gait analysis (QGA). Only surgical lower-limb amputations, for any reason, are discussed here.

2. Background

Amputation may be required in different indications:

- trauma: examples include crush injury to the limb due to a vehicle or injury by a farming machine or lawnmower (Fig. 1). The level of the amputation varies. The crucial point is adjustment to the level of the initial lesion;
- infection: *Purpura fulminans* with bloodstream infection is the most severe form (Fig. 2). This life-threatening condition requires emergency treatment and carries a high risk of amputation. In patients with gas gangrene, amputation is a life-saving procedure. In the event of infection, the amputation level should be determined with care, to obtain a cut in healthy tissue while preserving sufficient length of the residual limb. Failure to create a sufficiently wide safety margin between the initial site of

* Orthopédie pédiatrique, hôpital Couple-Enfant, CS 10217, 38043 Grenoble cedex 09, France.
E-mail address: jgriffet@chu-grenoble.fr

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Fig. 1. Lawnmower injuries.

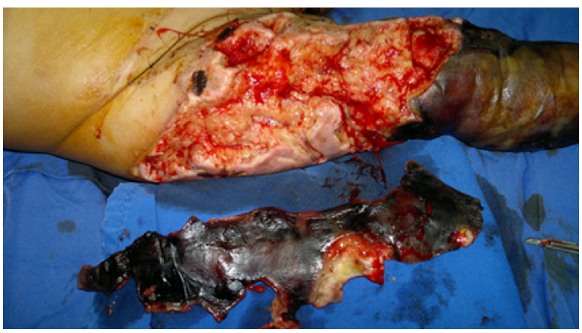

Fig. 2. *Purpura fulminans*.

infection and the level of amputation puts the patient at risk for recurrent infection;

- tumours (Fig. 3): this cause has become less common. Keeping a sufficiently wide safety margin between the tumour and the suprajacent cut is mandatory but may limit the length of the residual limb;
- congenital abnormalities: an example is congenital pseudarthrosis of the tibia. Amputation may be the only option in these conditions;
- vascular abnormalities: compromise of the vascular supply is rare in children. The main causes are iatrogenic vascular injury due to extravasation of contrast medium or drugs into the perivascular or subcutaneous compartment. Thrombosis is less common (Fig. 4). Amputation may be inevitable.

Fig. 3. Osteosarcoma of the distal third of the tibia in a 5-year-old.

Congenital amputation, or limb agenesis, requires a highly specific management strategy that does not involve surgery. This condition is not discussed here.

3. General principles of paediatric amputation surgery

Most of the amputation techniques used for adults are also suitable for paediatric patients. Attention should be given to the growth potential of the stump, which varies with the amputation level. Adaptation is best in the youngest children. The objective is prompt wound healing followed by fitting with an appropriate prosthesis that will allow the patient to resume near-normal activities.

Krajbich listed the general principles of childhood amputation surgery [1]:

- preserve limb length;
- preserve growth plates;
- prefer disarticulation over transosseous amputation;
- preserve the knee joint whenever possible;
- stabilise and normalise the proximal portion of the limb;
- direct appropriate attention to the patient's general health and to clinical conditions other than the amputation.

Preserving length is crucial in paediatric patients. Because the distal growth plate contributes 75% of longitudinal femoral growth, transfemoral amputation results in a very short final stump. Transtibial amputation preserves the growth plate but can result in bone overgrowth at the transected end, which may continue until growth is complete, often requiring trimming on one or two occasions. The fibula grows faster than the tibia and becomes prominent. Another possible complication in children after transfemoral or transtibial amputation is formation at the bone end of a sharp spur that gradually penetrates the overlying soft tissues. The best means of preventing this complication is tibiofemoral synostosis or typical osteomyoplasty [2]. When the fibula is absent, a number of techniques can be used, including extensive bone grafting, which carries a major risk of resorption; use of bone cement to fashion a champagne cork-shaped end; or stump capping using the inverted fibula, with the fibula diaphysis press-fit into the medullary canal and the head located distally, where it produces a pleasantly rounded stump end [3].

In every case, revision surgery may prove necessary, particularly to correct growth disorders. The child and parents should be informed of this possibility.

Fig. 4. Acute iatrogenic ischaemia.

4. Types of acquired amputation and disarticulation of the lower limbs

The procedures can be classified according to the level involved.

Inter-ilio-abdominal disarticulation is rarely performed (Fig. 5). Prosthetic fitting is difficult after this extensively mutilating procedure.

Hip disarticulation allows more effective prosthetic fitting in paediatric patients.

Transfemoral amputation (above-knee amputation) is performed:

- at the proximal third of the femur (Fig. 6) in most cases;
- or at the distal third of the femur (Gritti-Stokes amputation) [4]. This method is rarely used in children, because it severely impairs the growth potential of the limb by removing the distal femoral growth plate. In adolescents, in contrast, Gritti-Stokes amputation is a valuable procedure that allows application of the patella to the transected end of the femur, thereby creating a shock absorber.

Disarticulation of the knee is very rarely performed but can be useful to treat tibial tumours or birth defects.

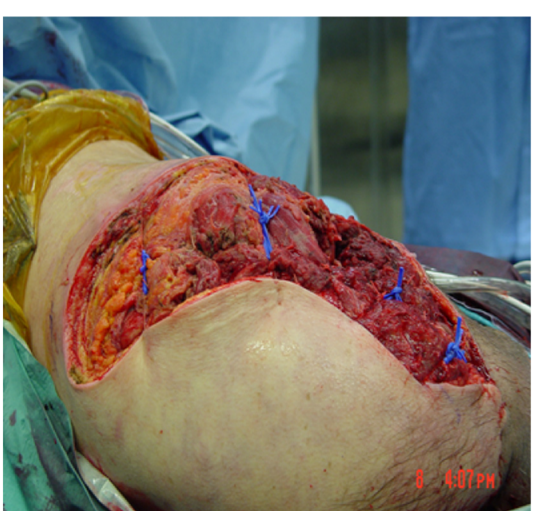

Fig. 5. Inter-ilio-abdominal disarticulation.

Fig. 6. Amputation at the proximal third of the femur.

Amputation at the proximal third of the tibia is now preferable, because it allows fitting of a satisfactory prosthesis with excellent long-term tolerance.

> When amputating the leg, resection of the antero-inferior aspect of the tibia should be achieved by cutting the diaphysis transversally at a 35° angle (Farabeuf's angle, Fig. 7). This point is crucial to avoid skin injury by the bone end. The anterior wedge of tibial cortex, which would carry a high risk of skin injury if left in place, can be used to occlude the medullary canal and to achieve haemostasis.

Foot amputations:

- with Chopart amputation through the midtarsal joint, a stable and painless stump allowing distal weight bearing must be obtained. The prosthesis extends to the knee. Arthrodesis of the hindfoot is mandatory, with or without talectomy [1];
- the functional impact of forefoot amputation is considered mild to moderate. Recurrent equinus is not infrequent. Tibio-talo-calcaneal or tibiocalcaneal arthrodesis with astragalectomy allows active patients to recover their full potential after fitting of an optimal prosthesis (Boyd amputation [5]);
- at the toes, limited necrosis requires amputation of the distal phalanx, whereas more extensive involvement of the great toe may require interphalangeal disarticulation; for the lesser toes, metatarsophalangeal disarticulation is preferable [1].

Fig. 7. Farabeuf angle (35°) for cutting the tibia.

For stump coverage after any type of foot amputation, preference should be given to controlled wound healing followed by transplantation of full-thickness skin grafts, which are more effective in accommodating growth during childhood compared to dermo-epidermal skin grafts. In some cases, free-flap coverage is the only option for salvaging the foot.

5. Changes in lower-limb prostheses and their impact on stump fashioning in paediatric patients

Overall efforts to improve sockets have pursued three goals:

- to increase the weight-bearing surface area in the socket;
- to eliminate friction at the skin-socket interface;
- to eliminate all lever effects between the socket and suprajacent segment.

The arrival on the market of new materials (e.g., silicone gels, co-polymers, and polyurethane) has contributed considerably to recent advances in prosthetic devices. Major innovations have occurred, requiring the development of new criteria for stump quality and optimisation. The quality of the stump now exerts a major influence on prosthesis function.

A discussion of the innovations relevant to each level of lower-limb amputation is needed to determine the stump length and shape associated with the best patient outcomes. Factors that guide decisions about stump fashioning include the space distal to the stump that is needed to accommodate the prosthesis best suited to the patient, not only at the time of the amputation, but also in adulthood, when growth will have changed the length of the limb segments.

5.1. Level 1: the hip

The patient sits on the ischial tuberosity on the amputated side. The ischial tuberosity can be guided into a containment socket to improve control. The prosthesis is suspended by a belt above the iliac crests.

The ischial containment socket accommodates the entire buttock on the amputated side and extends upwards by a belt that wraps around the hemi-pelvis on the opposite side. The anterior aspect should extend as close as possible to the pubis and ischiopubic ramus, both to leave enough space for the hip component and to provide a large bone-socket interface (Fig. 8).

Excessive padding of the amputated zone diminishes the ability to control the socket and prevents optimal positioning of the prosthetic hip joint axis (Fig. 9).

The quality of the interface impression and selection of the materials used contribute to improve patient comfort. The socket must leave the lumbosacral junction free, thus allowing sagittal tilting of the pelvis. This junction controls the prosthesis. The false ribs should not contact the socket when the patient is seated.

The prosthetic material (hip and knee) is lightweight but performs poorly in children (Fig. 10). This type of prosthesis allows harmonious walking on level ground (whereas uphill and downhill walking is difficult).

For children who have reached their final height, in contrast, high-performance prosthetic materials are available. They produce a more dynamic gait and allow a step-over-step gait pattern when walking down inclines or stairs. Running is possible but difficult (Fig. 11). Although these prostheses can provide good patient comfort during walking (with an ability to walk long distances), a perceptible limp persists and the device is cumbersome.

Few innovations have occurred for this type of prosthetic device.

5.2. Level 2: the femur (above-knee amputation)

This is the amputation level that has benefited the most from technological advances.

Previous sockets were quadrilateral and required severe tightening over the root of the stump, which caused deformation of the thigh by compression in the anteroposterior direction (Fig. 12). The tightness of the socket caused trophic changes in the stump that considerably limited the walking distance of the patients. This contact-type prosthesis was difficult to don and caused tissue trauma. Consequently, whenever possible, surgeons performed procedures allowing weight bearing on the stump end (knee disarticulation, Gritti-Stokes amputation) to prevent ischial tuberosity pain during walking.

Currently available solutions: innovations have occurred in two main areas.

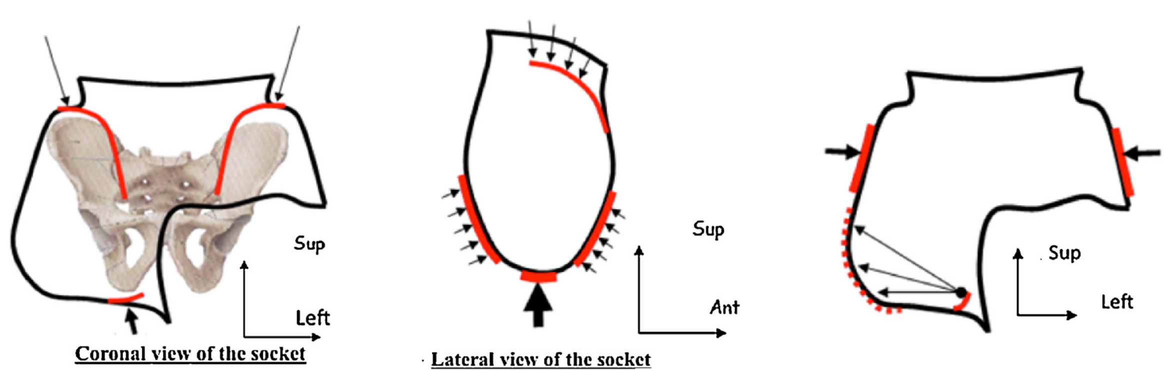

Fig. 8. The containment socket cups the buttock and extends by a belt to the hemi-pelvis on the opposite side.

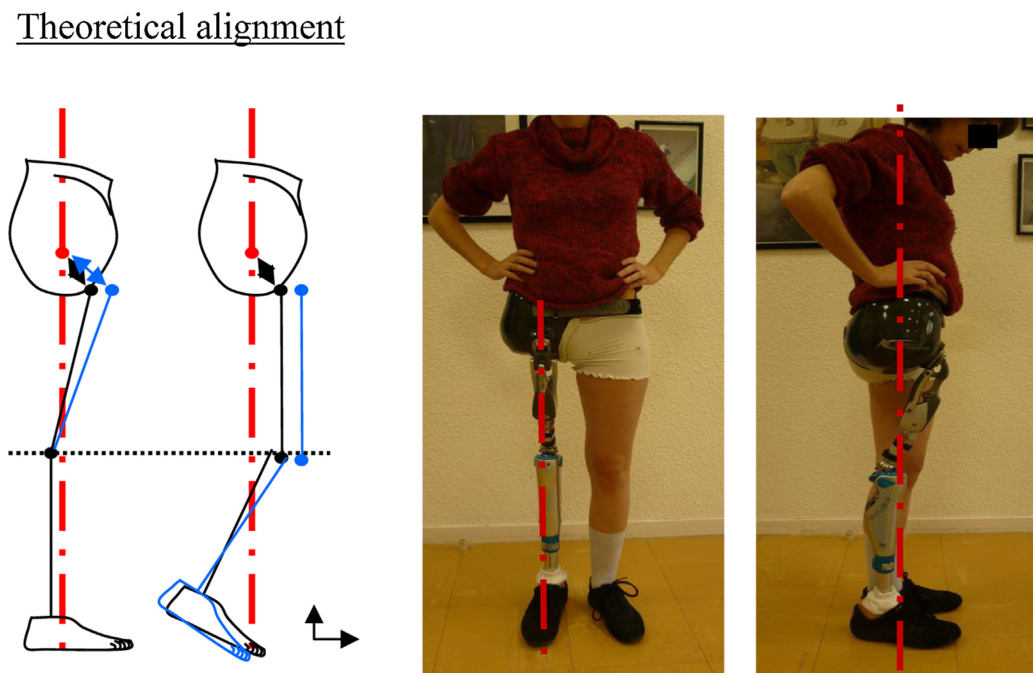

Fig. 9. Alignment of a total lower-limb prosthesis.

5.2.1. Shape of the socket

The new sockets cup the medial aspect of the ischial tuberosity (integrated ischium). This design allows excellent socket control without proximal tightening or marked weight bearing on the tip of the ischial tuberosity. The femur is applied against the lateral aspect of the socket and therefore provides more accurate control of the prosthesis (Fig. 13).

Another advantage of this concept is that the femur is returned to its physiological adduction position. Thus, the hip can be extended without putting excessive pressure on the ischial tuberosity and, therefore, without inducing compensatory lordosis (Fig. 14).

These sockets, when well fashioned, are extremely comfortable and provide a walking distance close to that achieved by able-bodied individuals. Their better tolerance to stump-size increases make them very well suited to paediatric patients. The tightening force should decrease from the end to the root of the stump, in order to avoid compromising the vascular supply. The absence of tightening at the socket collar contributes to increase the range-of-motion gains of the fitted thigh.

5.2.2. Use of an adhesive interface (silicone) to cover the stump

A sleeve is used to control tightening over the stump (Fig. 15). The sleeve is rolled on, starting at the stump end. It adheres to the

Fig. 10. Lightweight prosthesis in a child: change in hip joint position, knee with a locking or braking mechanism assembled in hyperextension, dynamic carbon-fibre foot.

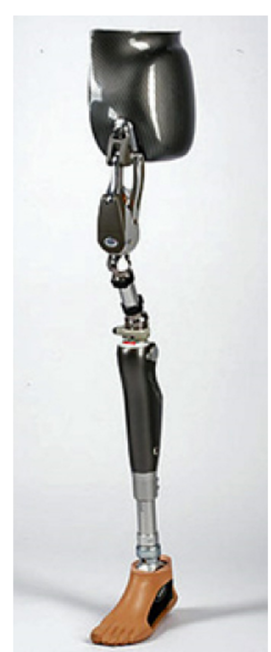

Fig. 11. High-performance prosthesis comprised of a Helix 3D hip joint, a C-LEG microprocessor-controlled knee, and a dynamic carbon-fibre foot.

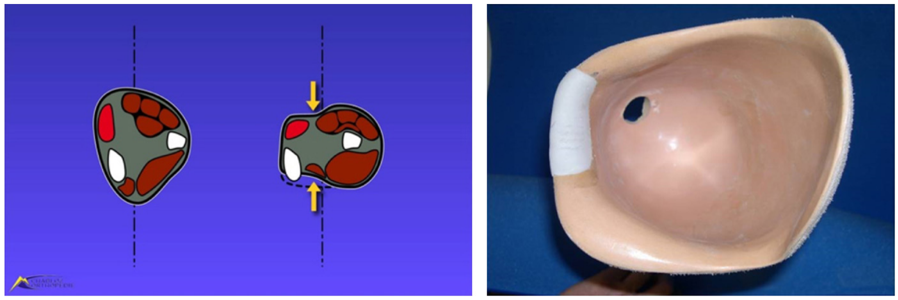

Fig. 12. Early-model quadrangular socket designed to be tightened in the anteroposterior direction.

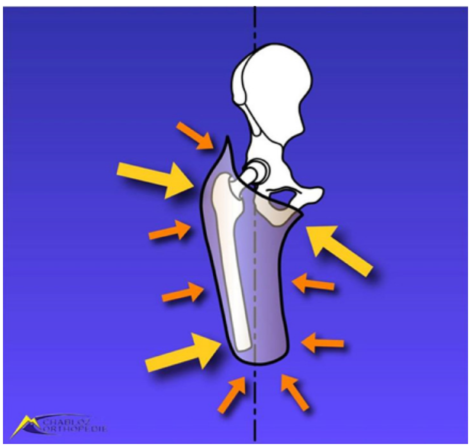

Fig. 13. New generation “integrated ischium” socket.

stump and positions the compressed soft tissues into the shape required to accommodate the rigid socket.

Advantages of the adhesive silicone interface include:

- easy donning of the prosthesis;
- adhesion to the stump with elimination of friction at the skin-socket interface;
- beneficial effects on the scar (smoothing and softening);
- optimal pressure distribution over the entire stump surface, with increased patient comfort.

A silicone gel pad can be added at the end of the stump, for instance when the end of the femur is excessively prominent.

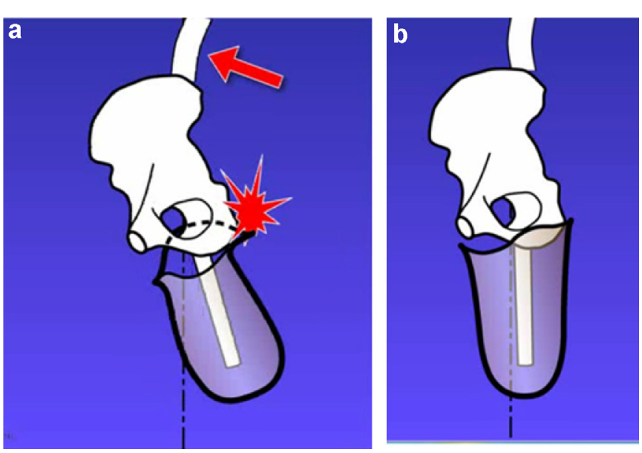

Fig. 14. (a) quadrangular socket that impinges on the ischium, precluding hip extension; (b) “Integrated ischium” socket allowing hip extension.

Fig. 15. Silicone sleeve.

Care should be taken to ensure that no air is trapped between the skin and the sleeve (due to an invaginated scar). Air pockets create suction, which produces blisters.

This new socket design requires a reappraisal of the criteria used to define the optimal stump

A well-shaped scar must be obtained (without pitting or invagination).

- Preserving volume over the stump is unnecessary and can result in a pseudarthrosis-like phenomenon between the femur and the socket. A slender stump end allows better control of the prosthesis.
- If possible, a pad of soft tissue (3–4 cm in thickness) should be preserved distal to the end of the femur to improve comfort during weight bearing; (the pad is stabilised by the sleeve).
- The length of the stump should leave enough room for the prosthetic knee (the distance from the stump end to the knee joint axis should be 4–5 cm in paediatric patients and about 10 cm in adults).
- Stumps consistently perform well if they end between the middle third of the thigh and the required distance given above.
- Importantly, the stump length includes the thickness of the soft tissues left under the end of the femur, and compression by the sleeve consistently lengthens the stump by 1–2 cm.
- Because the ischial tuberosity is cupped in the socket, even a short stump (10 cm) is perfectly serviceable.

Fig. 16. C-LEG® OttoBock knee that allows the wearer to walk downstairs. This device is reimbursed by the French statutory health insurance system.

Combining an adhesive sleeve and an integrated-ischium socket provides the patient with sufficient comfort and control over the prosthesis to achieve walking distances nearly equal to those of able-bodied individuals. The subsequent functional capabilities of the patient depend on which prosthetic devices are available and actually used.

Available prosthetic knees suitable for the weight and height of children have limited functions. They allow alternate ambulation but offer no assistance for walking down inclines or stairs, and are even less helpful for walking up.

However, their considerable adaptability allows children with sufficient stump length to easily manage any situation despite a simple knee design. Some children even learn to climb stairs.

As the child grows, the array of available prosthetic devices and technical aids broadens. Pre-flexion of the knee at the heel-strike phase can even be replicated, thus improving comfort via a slight shock-absorbing effect. With specialised rehabilitation therapy, the patients can learn to walk down inclines or stairs, with only limited muscular effort (C-LEG® Ottobock knee, reimbursed in France by the health insurance system) (Fig. 16).

The prosthesis can be equipped with a shock absorber to improve comfort, a torque absorber for playing golf, and even a rotator at the knee to permit cross-legged sitting (Fig. 17).

New prosthetic knees that allow stair climbing are becoming commercially available. They combine a gyroscope and microprocessors (Genium®, Ottobock, not reimbursed by the French statutory health insurance system) (Fig. 18). They provide extremely natural assistance in all situations and hold considerable promise for the future.

Fig. 18. The Genium® knee (Ottobock) combines a gyroscope and microprocessors to allow the wearer to climb up stairs.

The comfort provided by the new sockets combined with running blades (not reimbursed) allows even the youngest patients to run easily. Many sports are possible with a femoral prosthesis, although a specific device may be required (Fig. 19). A specific knee-foot combination is available for alpine skiing and snowboarding.

5.3. Level 3: the tibia (below-knee amputation)

5.3.1. Gentler socket shapes and adhesive sleeves

Remarkable functional outcomes have always been obtained after tibial amputation. The tolerance of prostheses for below-knee

Fig. 17. (a) Knee with a rotator; (b) Knee with a torque absorber.

Fig. 19. Prostheses designed for specific sporting activities: (a) running; (b) biking; (c) snow sports.

amputation has benefitted considerably from the development of total-contact sockets (Total Contact Bearing [TCB]). Total-contact sockets are fashioned over a thin adhesive or 6-mm gel sleeve and are combined with a ratchet or vacuum suspension system. This design completely eliminates friction while reliably holding the prosthesis in place. Furthermore, pressures are uniformly distributed in a socket characterised by a gentle physiological shape and uniform tightening (Fig. 20). The patient is no longer exposed to infrapatellar and popliteal overloading, with its attendant complications (Fig. 21).

Total-contact sockets are always used over an adhesive sleeve, which is an integral part of the system and is rolled onto the stump, as with femoral prostheses. Sleeves come in various sizes, materials (silicone, co-polymers, and polyurethane), and thicknesses (Fig. 22). They can also be custom-made based on a mould if required by the shape of the stump.

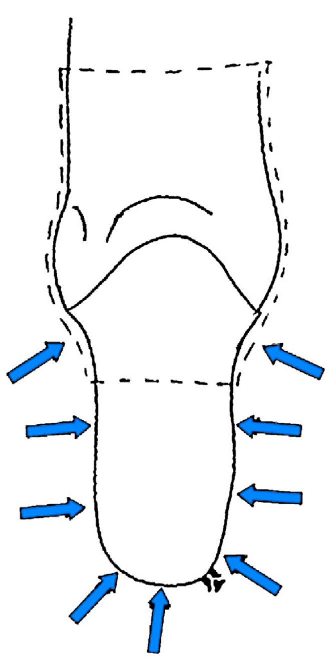

Fig. 20. Total-contact socket (Total Contact Bearing) tightened uniformly around the stump.

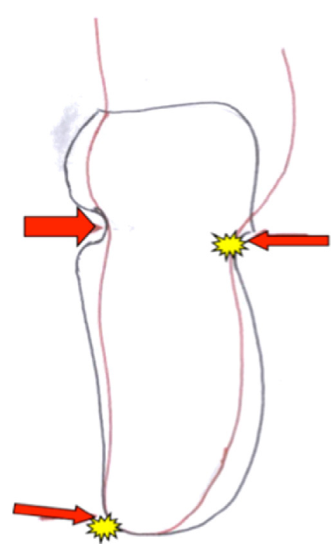

Fig. 21. Early-model below-knee socket responsible for overloading of the infrapatellar and popliteal zones.

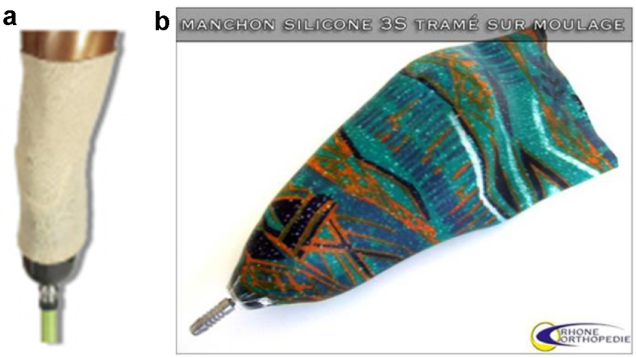

Fig. 22. Sleeves: (a) ready-made; (b) fashioned over a mould.

Fitting of the prosthesis in flexion is no longer mandatory and a more physiological limb is thus produced.

5.3.2. *In paediatric patients*

The uniform pressure distribution and easy donning of the prosthesis with a sleeve that is rolled onto the stump reassure the child and parents. Habituation to the prosthesis usually raises no difficulties.

The absence of a mechanical suspension mechanism proximal to the condyles may promote good development of the quadriceps, with a smaller decrease in thigh circumference. The shape of the socket avoids excessive pressure on the patellar tendon.

This type of prosthesis can be used as early as 8 months of age, as soon as the infant starts trying to pull up to the standing position (Fig. 23).

With advancing age, bone growth requires two additional surgical procedures on average.

5.3.3. *Current level of autonomy of tibial amputees*

Today, a below-knee amputee with a good-quality stump can have the same lifestyle and engage in the same activities as an able-bodied individual. Only patients with extreme challenges fail to achieve this outcome. Thus, in most cases, the performance of the prosthesis used for everyday activities allows a normal life. This good performance becomes apparent at a very early age.

In France, most below-knee prostheses are fully reimbursed by the statutory health insurance system. The exceptions are highly specific devices designed, for instance, for skiing or running (Fig. 24).

Skin-like covers are available to improve cosmesis but are not reimbursed (Fig. 25).

Implications of the new socket designs for below-knee amputees on criteria used to define the optimal stump

As with above-knee amputation, excess flesh over the stump end is best avoided, to prevent a pseudarthrosis-like phenomenon between the stump and the socket.

The length of the stump should not exceed 20 cm distal to the tibiofemoral joint space in adulthood, to allow fitting of the highest-performance foot prostheses. The fleshy pad over the end of the stump should be counted as part of the stump length.

A stump 15 cm in length is sufficient to obtain a high level of performance, as the leg extensor and flexor muscles are located at the proximal part of the leg. Thus, stump length influences control but not strength of the stump.

As stated above, control is greatly improved with the new-generation sockets. Therefore, the trade-off is in favour of a shorter stump with a more favourable shape and a thicker soft-tissue pad over the bone end (it should be borne in mind that the loads are distributed uniformly over the entire surface of the stump, including the stump end).

When the stump must be shorter than 10 cm, one option consists in using a moulded silicone-gel pad over the stump end, which is included within the sleeve, to improve the lever arm and maximise patient comfort.

The fibula must always be shorter than the tibia (by about 3 cm). However, removing the fibula negatively affects prosthesis control in rotation.

The tibial end should be rounded and cut according to Farabeuf's angle.

A vast array of prosthetic materials is available for these prostheses.

Patients can benefit not only from a broad range of dynamic carbon-fibre feet, but also from shock absorbers, torque absorbers, and feet specifically designed for skiing or water sports. Below-knee prostheses are consistently more versatile than above-knee prostheses.

5.4. *Level 4: the foot*

Transtarsal amputations consistently raise problems, even when arthrodesis is performed. The prosthesis must extend up over the leg to ensure at least a minimum level of performance (Fig. 26). It is always unsightly, although the patient remains able to bear weight on the ground when not wearing the prosthesis.

Cosmetic foot prostheses can be fashioned but fail to ensure function.

Patients with transmetatarsal or partial forefoot amputation are often able to walk without a prosthesis. Functional outcomes are optimal with a silicone prosthesis: this device not only acts as an

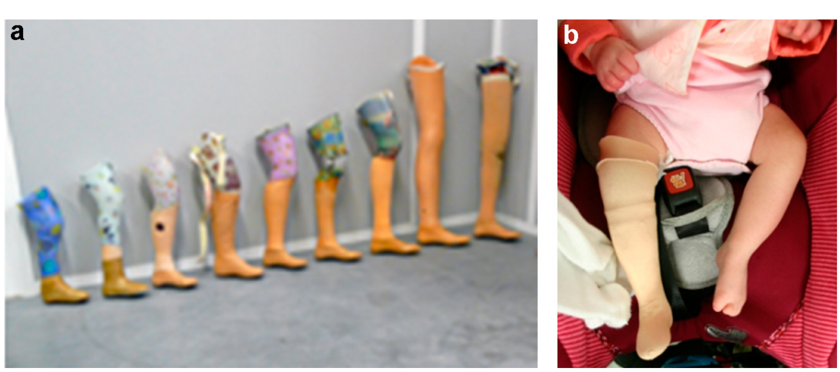

Fig. 23. (a) Range of prostheses for paediatric patients; (b) prosthesis worn by an 8-month-old infant.

Fig. 24. Various types of prosthetic feet.

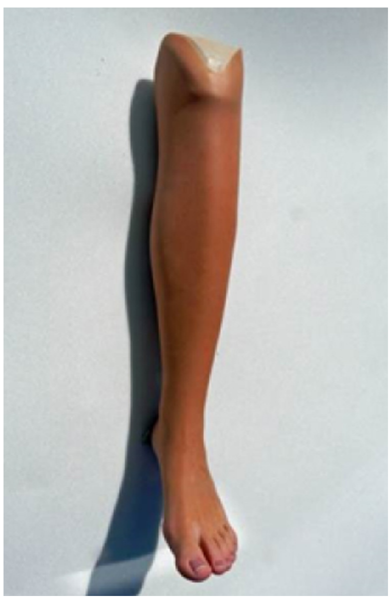

Fig. 25. Cosmetic cover.

orthopaedic insole that ensures appropriate weight-bearing distribution, but also compensates for the missing volume, thereby helping to stabilise the residual foot while improving cosmesis. Adding a thin carbon-fibre plate can enhance dynamic function. Nevertheless, the prosthesis does not always provide the same level of performance and reliability as a below-knee prosthesis.

In our experience, this type of amputation raises multiple problems in some patients, particularly in children during the growing period.

6. Adjusting the prosthesis

To maximise comfort, function, and durability, optimisation of weight-bearing distribution, alignment axes, and gait kinematics is essential. The patient should be able to walk safely in the greatest possible number of situations, not only on level ground but also over rough terrain, while going up or downstairs, and when running or engaging in sporting activities, even at a high level. To achieve this objective, modern tools must be used, namely, three-dimensional lower-limb imaging (EOS) and quantitative gait analysis (QGA).

6.1. Three-dimensional lower-limb imaging

The EOS imaging system provides images of the standing patient that show the entirety of the lower limbs and spine, in the anteroposterior and lateral projections. On the whole-body view, three-dimensional reconstruction of the skeletal components allows an evaluation of overall alignment. The actual lower-limb axes can be determined and the prosthesis adjusted to preserve these axes [6]. Length can also be adjusted. These adjustments ensure good anatomic adaptation of the prosthesis (Fig. 27).

Fig. 26. Foot prostheses.

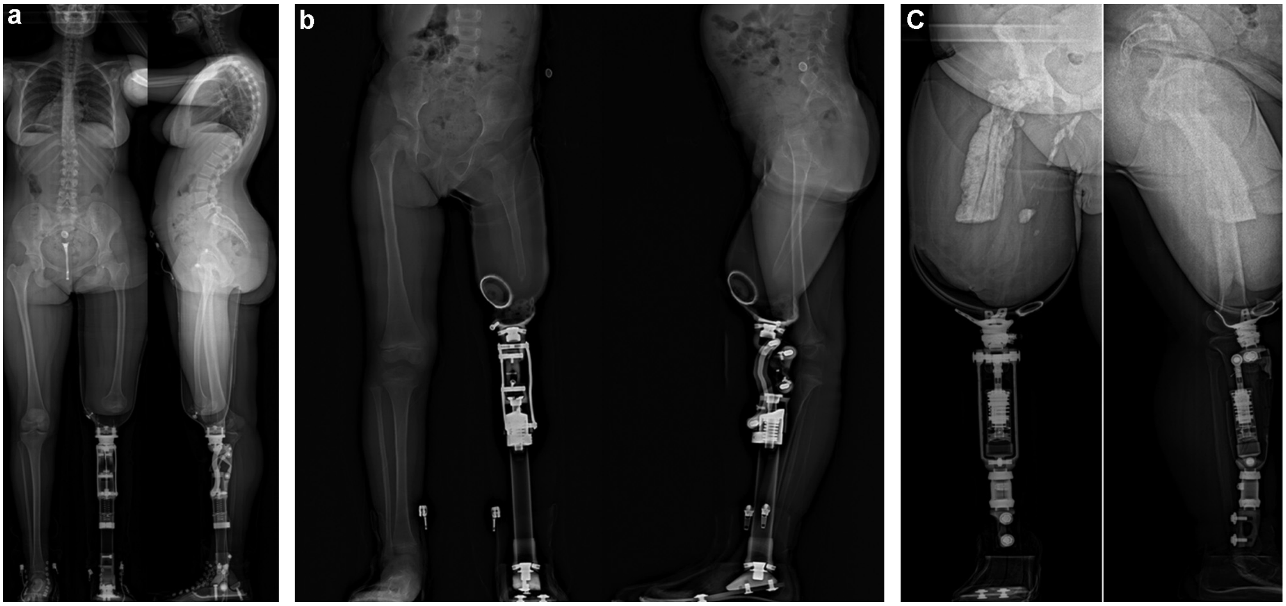

Fig. 27. EOS radiographic imaging. (a) Whole-body view to evaluate alignment (knee disarticulation in a patient with birth defects); (b) above-knee amputation in a child; (c) amputation in a young adult (melorheostosis diagnosed at 15 years of age).

Parameters		Functional Ambulation Profile: 96	
Distance (cm)	2086.9	Cadence (Steps/Min)	105.5
Ambulation Time (sec)	15.93	Step Time Differential (sec)	.08
Velocity (cm/sec)	131.0	Step Length Differential (cm)	.02
Mean Normalized Velocity	1.58	Cycle Time Differential (sec)	.01

Parameters		Functional Ambulation Profile: 91	
Distance (cm)	1982.8	Cadence (Steps/Min)	106.8
Ambulation Time (sec)	14.05	Step Time Differential (sec)	.08
Velocity (cm/sec)	141.1	Step Length Differential (cm)	1.76
Mean Normalized Velocity	1.70	Cycle Time Differential (sec)	.00

Fig. 28. Spatiotemporal parameter measurement (GaitRite®) providing the Functional Ambulation Profile (FAP, score on 100): the FAP score was 91 with a C-Leg® knee and 96 with a Genium® knee.

6.2. Quantitative gait analysis (QGA)

The static analysis shows the load distribution over the points of contact with the ground (axes and pressure on the ground).

The dynamic analysis involves measuring both kinematic and kinetic criteria (Fig. 28). Kinematic data allow optimal prosthesis adjustment, particularly for bringing the lower limb forward during the swing phase and, at the knee, for providing shock absorbance during the heel-strike phase (Fig. 29). Kinetic studies assess the impact of the prosthesis on the joints, in particular via the measurement of moments, and allow the adjustment of foot rotation to optimise the lever arms (Fig. 30).

The Gait Real-Time Analysis Interactive Lab (GRAIL) is a particularly useful tool that allows gait analysis in a variety of situations with real-time display and immediate feedback (Fig. 31). Adjustment of the "electronic knee" is optimised by simulating walking

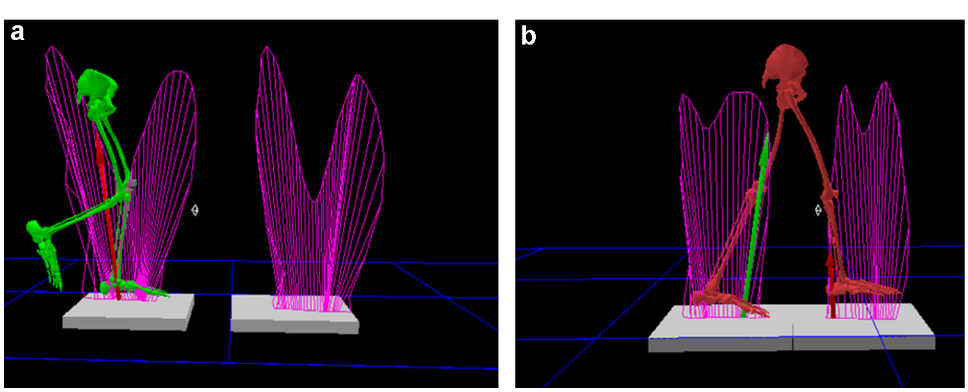

Fig. 29. Kinematic data recorded during walking. (a) the gait pattern is more jerky with the C-Leg® knee; (b) the Genium® knee provides a smoother gait pattern.

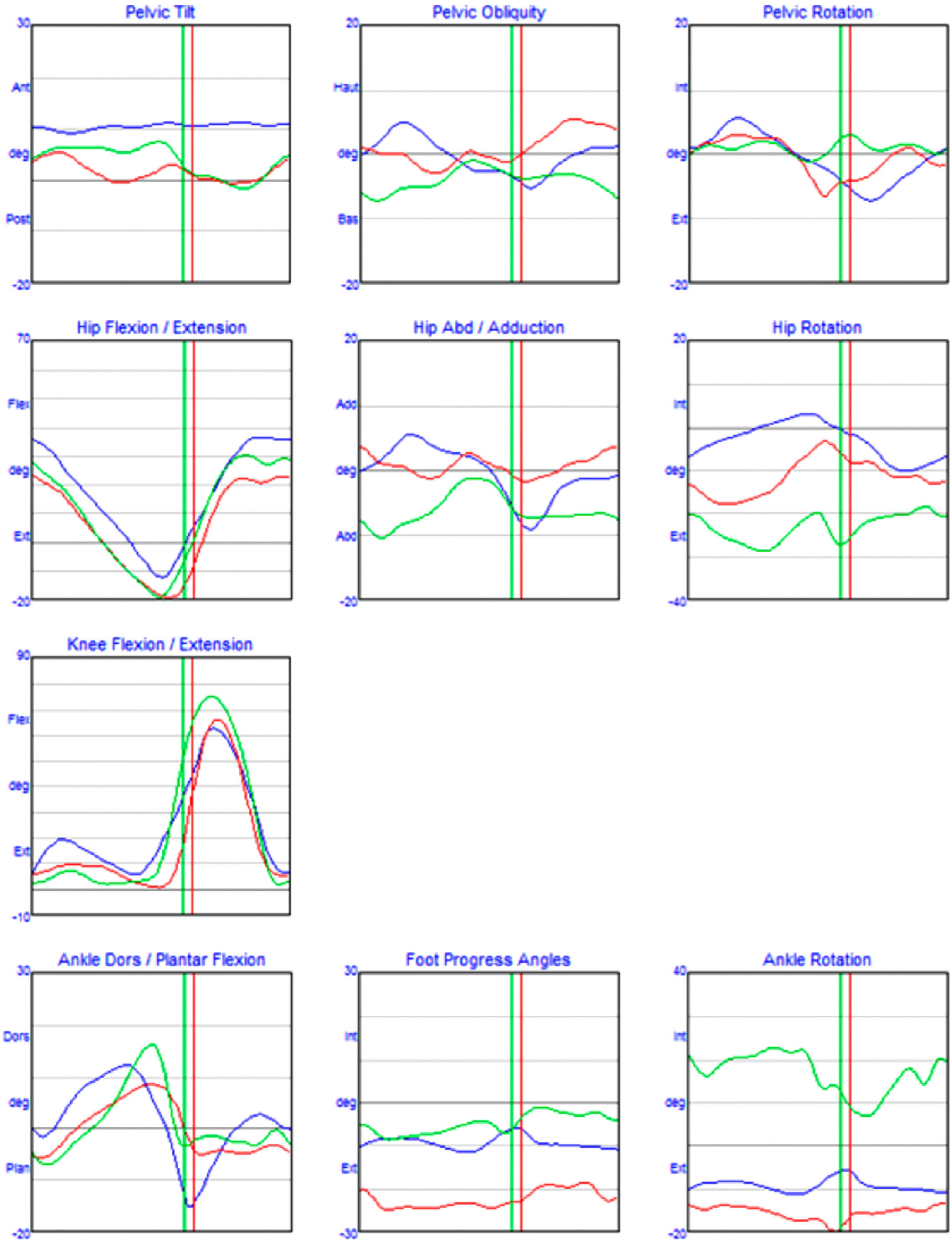

Fig. 30. Dynamic gait analysis: normal curve in blue, Genium® knee in red, and C-Leg® knee in green. The Genium® knee best replicates the normal gait.

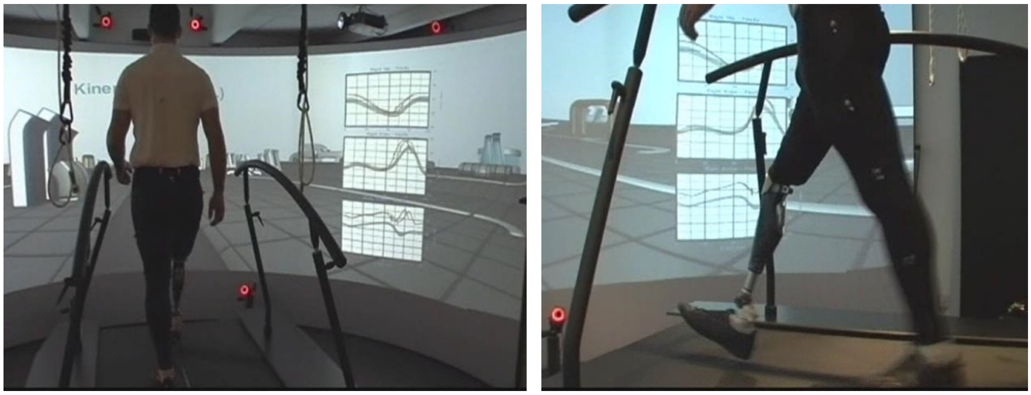

Fig. 31. Gait Real-Time Analysis Interactive Lab (GRAIL): readaptation with feedback.

over a variety of terrains, thus improving patient safety. The optimal duration of unlocking while descending stairs can be determined.

7. Evaluations, rehabilitation objectives, and implementation modalities [7–10]

7.1. *Initial phase: early management after the amputation*

Ideally, the child and family meet with the PRM department staff before the amputation. During this visit, the staff provides information and as much reassurance as possible regarding future function with a prosthesis. After the amputation, PRM management usually occurs on an inhospital basis, since the healthcare interventions must be adjusted several times a day.

Immediately upon admission, the child is met by the members of the team, who conduct the initial evaluation: medical history; circumstances of the amputation; concomitant lesions in patients with multiple fractures or other injuries; general health (e.g., loss of exercise fitness, infections, anaemia related to trauma or chemotherapy, neutropenia); level of the amputation and whether the limb loss is bilateral; local condition of the stump, particularly the characteristics of the scar and presence of stump oedema; range of motion of the suprajacent joints; self-sufficiency; and psychological status.

Objectives during this initial period are as follows:

- prevention of immediate postoperative complications and complications of immobility;
- installation in the bed and wheelchair;
- monitoring of stump wound healing;
- management and prevention of pain, particularly neuropathic pain [11];
- prevention of fixed postural abnormalities (flexion contractures);
- preparation of the stump for prosthesis fitting.

Simultaneously, the patient must be helped to regain self-sufficiency for getting around and performing activities of daily living. Furthermore, psychological support must be provided. A number of interventions are used to reach these objectives:

- nursing care: help with bathing and hygiene, dressing changes, compressive stump bandages with a Bi-Flex compression bandage initially, then an elastic sleeve cut to size, and daily evaluation of pain intensity and of the analgesia protocol;
- physical therapy: stump drainage, manual or mechanical scar treatment, prevention of adhesions, joint mobilisation, corrective postures, gradual assumption of the erect posture on the table, and practice in using the wheelchair, which contributes to exercise retraining;
- psychotherapeutic support, started as early as possible to help the patient integrate the amputation within his or her life story and psychological identity;
- educational support, via assistance in regulating interpersonal relationships during everyday life, channelling emotions as they arise, engaging in recreational activities and, finally, returning to school, if needed on a part-time basis; the educational, nursing, and child-care staff initiate, then support the child's participation and listen carefully to the child while delivering care in order to identify episodes of distress and anxiety.

7.2. *Prosthesis fitting phase*

This phase contributes substantially to improve the patient's outlook by restoring self-sufficiency, the ability to stand and, gradually, the ability to walk. Prosthesis fitting is also the most effective treatment of phantom limb pain and, during this phase, the analgesics started postoperatively can be progressively decreased.

Prosthesis fitting involves several steps, depending on changes in the stump and on the presence of other injuries that often require the fabrication of a variety of provisional devices.

Locomotion is promoted by encouraging the patient, then providing gait and balance training in order to restore self-sufficiency. Participation in sports should be discussed if appropriate. Teenagers often attach considerable importance to sporting activities, and the attention given by the media to amputees who win competitions helps to rebuild a positive self-image. This is the appropriate time to put the patient in contact with organisations of amputees, who can share their own experience.

This period requires close monitoring of pressure points in the socket, first by all the members of the healthcare and rehabilitation team, then by the patient or parents.

The rehabilitation programme includes muscle strength exercises, balance exercises, and work on the gait pattern with the prosthesis in place, first between parallel bars, then with a crutch and, finally, without a crutch. Exercise retraining should be continued and intensified. The patient can then learn gradually to run and to jump.

There are few contraindications to prosthesis fitting. Contraindications may be related to neurological or psychological factors. Orthopaedic contraindications consist of fixed contractures or abnormalities of the upper limbs or other lower limb. Finally, there may be a vascular contraindication with a probable need for contralateral lower-limb amputation in the short term.

7.3. Adaptation phase

The adaptation phase aims to restore full self-sufficiency for activities of daily living. The patient should receive education in stump care; donning the prosthesis; caring for the sleeve; managing skin problems such as friction, redness, and skin abrasions; and managing changes in stump shape. Arrangements should be made to prepare for life after hospital discharge, including the return to a regular school with an individually tailored educational programme and the resumption of social activities such as sports and other recreational pursuits.

As an alternative to inpatient care, if allowed by the familial, architectural, and healthcare environment, the patient may be managed at home with visits by various healthcare providers. Other options consist of a sequence of outpatient visits, day-hospital care, and outpatient monitoring jointly with the prosthetist.

In France, amputees are entitled to a number of benefits. Their level of disability is rated at $\geq$ 50% or even $\geq$ 80%. The parents receive disability benefits and may be entitled to additional sums depending on the expenses entailed by the disability. If required for attendance at a regular school, the child may be entitled to a school helper. The social services should be contacted to assess the child's rights and meet the authorities' requirements in terms of social, administrative, and medical information. Furthermore, in France, amputees are entitled to full reimbursement of all healthcare services related to the amputation. Arrangements should be made as early as possible to obtain full-reimbursement status, to facilitate both inhospital care and prosthetic fitting. All prostheses except those specifically designed for sports are fully reimbursed by the French statutory health insurance system.

8. Long-term follow-up

8.1. Visit to the PMR department once or twice a year depending on age and period of growth

The morphostatic development of the child amputee must be monitored. Throughout growth, the impact of the amputation on spinal and pelvic alignment must be evaluated, as well as the leg-length discrepancy. Patients should be asked about pain. Range of motion of the joints suprajacent to the prosthesis should be measured.

8.2. Changes in the prosthesis

The prosthetic requirements change as the child grows, and the device should be changed as often as needed, usually once a year. In most cases, the change can be performed on an outpatient basis.

The prescription of new-generation prosthetic knees and fitting of a prosthesis designed for sports requires a specific evaluation followed by a 2-week trial in a specialised department equipped with the appropriate technical resources (e.g., quantitative gait analysis, treadmill walking, exercise testing, test circuits).

8.3. Psychological development over time

No published data are available on psychological outcomes after amputation in childhood or adolescence. The pattern of psychological adjustment described in adults may not apply to the paediatric age group. In particular, young children often adapt surprisingly well and suffer predominantly from separation anxiety. Teenagers and even pre-teens, in contrast, are distressed by the difference with their peers, even when their functional limitations when wearing the prosthesis are minimal. A high degree of vigilance is crucial and psychotherapy should be started early, although adolescents may be reluctant to accept this intervention. It should be borne in mind that the grief process may be delayed.

9. Evaluation

9.1. Gait assessment

Gait while wearing the prosthesis should be evaluated on a force platform.

9.2. Evaluation of quality of life and prosthetic fitting

Evaluation scales are not only indispensable for clinical research, but also necessary in clinical practice, as patients do not always share their everyday experience during medical visits. Many scales have been validated in children and adults. They assess a number of factors:

- pain: generic scales are usually satisfactory;
- functional capabilities (balance, walking speed, comfort during walking, and walking outdoors). The Houghton scale, which has been validated in French, evaluates walking, use of the prosthesis, walking outdoors, and walking over different types of terrain. This questionnaire, which is easy and rapid to administer, is highly sensitive to change, distinguishes between above-knee and below-knee amputees, and has been used in bilateral amputees. The Child Amputee Prosthetics Project-Functional Status Inventory for Toddlers (CAPP-FSIT), Child Amputee Prosthetics Project-Functional Status Inventory for Preschool children (CAPP-FSIP), and Child Amputee Prosthetics Project-Functional Status Inventory (CAPP-FSI) are validated and reliable tools designed for patients with limb agenesis. However, they are not available in French;
- quality of life: in addition to generic instruments for assessing quality of life in paediatric patients, a useful tool is the Orthotics and Prosthetics Users' Survey (OPUS), which is a self-administered questionnaire designed to evaluate function with and without the prosthesis, quality of life, and satisfaction with health services and devices (prostheses and orthoses), in children and adults. It has 64 items with four or five response options per item;
- psychological impact: projective tests (Rorschach inkblot test), depression scales, clinical evaluation, relationships, integration at school, sleep quality, appetite, and evidence of anxiety (whether expressed in words or otherwise). The results of the psychological evaluation may indicate a need for specific treatment.

10. Conclusion

Advances in lower-limb prostheses have considerably improved the self-sufficiency of amputees. The care directed to obtaining an optimal stump strongly influences the functional outcome. It is of the utmost importance that surgeons understand the consequences of the amputation procedure in order to optimise the potential for effective prosthetic substitution. Close collaboration between the PRM physician and prosthetist is crucial.

Adaptation of the prosthesis and support for overcoming psychological and social difficulties are best achieved during inpatient care in a PRM department, by a team of physicians, other healthcare professionals, social workers, and educators, with the use of evaluation tools such as EOS® imaging and quantitative gait analysis.

Disclosure of interest

The author declares that he has no competing interest.

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