Ten-Year Follow-Up of Lower Limb Replantation

Objective Evaluation With Gait Analysis

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Abstract: The decision-making process for lower limb replantation involves several critical factors, such as age, comorbidities, ischemia time, type of injury, and psychosocial considerations. Advances in microsurgical techniques have led to a greater focus on enhancing functionality through limb salvage. To improve functional outcomes, it is essential to gain a better understanding of the current challenges in reconstruction and address them in future cases. Objective functional analysis of lower extremity replantation cases holds the potential to guide us in this endeavor. In this report, we present a lower limb replantation case with a 10-year follow-up, including objective functional evaluation with gait analysis.

Key Words: foot replantation, lower limb salvage, amputation, gait analysis

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Lower extremity traumatic amputations are mostly caused by high-energy workplace accidents, and decision of replantation or revision amputation of the amputated lower extremity remains challenging.[1–3] Various trauma scores, such as the Predictive Salvage Index, the Mangled Extremity Severity Score, and the NISSSA (Nerve injury, Ischemia, Soft tissue injury, Skeletal injury, Shock, Age of patient), have been developed to predict the outcomes of the surgical treatment and guide the decision on the indication for replantation.[4–6] However, decision making for amputation with these scoring systems is difficult. In addition to the insufficiency of lower extremity trauma scores,[7] the high postoperative complications rates, difficulties in microsurgical techniques, poor functional outcomes, and the need for multiple secondary corrective surgeries in lower extremity replantation make the procedure discouraging.[8,9] Moreover, current prostheses for lower limb amputation are very convenient with functional outcomes.[10] The more experiences with objective outcomes are shared, the fewer debates there will be on leg replantation. The proper evaluation of function in replanted limbs will help us introduce optimal treatment for these patients and make us understand the problematic parts of the reconstruction for the refinement of our surgeries. Gait analysis provides chance to objectively evaluate functional outcomes.[11–16] Here, we share our experience with a patient who underwent unilateral foot replantation, presenting long-term clinical and functional outcomes along with gait analysis results.

CASE REPORT

A 17-year-old fisherman underwent a right lower limb amputation following an entanglement in a hawser, resulting in an avulsion from 10 cm above his ankle joint. The injury involved localized crush injury with avulsed muscle strips on the amputated part (Fig. 1). Despite the extensive zone of injury and tissue crush with avulsion, considering the young age of the patient and discussions with the patient and parents, a decision to perform replantation was taken. After receiving tetanus toxoid, aspirin, and intravenous antibiotics, the patient was taken into the operating room.

The amputated part and the leg stump were irrigated with saline and chlorhexidine. The nonvital tissues were carefully debrided, and the neurovascular structures are identified. Avulsed segments of the nerves and vessels were resected until normal tissues were reached. The distal and proximal bone stumps were shortened 1 and 4 cm, respectively, and bony fixation was accomplished with a bone plate. Three screws were placed into the distal segment, and 4 screws were placed into the proximal segment (Fig. 2A); the fibula was not fixed.

A saphenous vein graft was harvested from the contralateral limb and used as an interpositional reverse vein graft in arterial and venous anastomosis (5 cm for venous and 10 cm for arterial anastomoses). The anterior tibial artery, posterior tibial artery, and 2 superficial veins were anastomosed using interrupted 10-0 nylon sutures. The circulation and perfusion of the foot were ensured by checking capillary refill from each toe before repairing other structures.

The distal and proximal ends of the tibial nerve were marked with prolene suture and ligaclip for the second operation. Anterior tibial and sural nerves were found to be severely avulsed, making repair impossible. Anterior, posterior, and lateral muscle groups and tendons were primarily repaired, along with closed fasciotomy, and the skin was sutured (Fig. 2B). The total ischemia time was 6 hours, with 2 hours of warm ischemia. Low-molecular-weight heparin was administered for 5 days, and cefotaxime 2 g per day was administered for 10 days. No vascular compromise or infectious problems were observed.

The patient was discharged from the hospital 10 days after the replantation with a posterior plaster splint with leg elevation and physical therapy for ROM. The patient started partial load or weight bearing on his food at 6 weeks and full weight bearing at 6 months, using a 2-inch lift on that shoe.

The second operation was performed 6 months later for the removal of the plate-screw system and the repair of the tibial nerve with a sural nerve graft. At the 10-year follow-up, functional evolution was conducted using gait analysis and clinical evaluation, including Semmes-Weinstein test and 2-point discrimination test for sensory recovery. No other corrective surgery was performed.

Gait Analysis

Functional evaluation was performed 10 years postoperatively. The gait patterns of the patients were studied using 3-dimensional motion analyses with Vicon 512 and Polygon Report System (Myrddin Technologies Ltd., USA). Our laboratory's Vicon-512 setup includes 7 infrared Vicon cameras with a maximum frame rate of 50 Hz, two 6-component AMTI 1000 force platforms, a 16-channel electromyograph Noraxon FM (Frequency Modulation) transmitter, and 2 digital video cameras for movie capture. The signal is digitized and stored by a personal computer using Vicon Clinical Manager (VCM).[17–19]

Thirty-three reflective tracking markers were applied to the whole body of the patient, following the guidelines described in the

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FIGURE 1. Left foot amputation secondary to crush/avulsion injury at distal leg level. Avulsion of the posterior compartment muscles can be seen in the left lower panel. Posterior tibial vessels and tibial nerve avulsion (arrow) can be seen in the right lower panel.

Vicon Clinical Manager software manual. These markers were tracked during a static data trial and during "dynamic" data trials to calculate virtual joint center locations. The patient walked on a 10-m-long route that passed through 2 force platforms at least five times. Several representative gait cycles from each trial were recorded, and at least 10 gait cycles were used for analysis by the Polygon report program. Joint movements, including rotations, were calculated in 3 planes for the hip, knee, and ankle joints. Step parameters, such as cadence (number of steps you take in 1 minute), double support, single support, foot off, opposite foot contact, opposite foot off, step length, step time, stride length, cycle time, and walking velocity, were also obtained. Flexion/extension, abduction-adduction, and rotational values were all graphically traced by the Vicon Clinical Manager software. Dynamic podography was conducted using a computerized dynamic footprint and motion analysis system (Musgrave footprint, Preston Communications Ltd., Dublin, Ireland).[20]

RESULTS

Clinical

We achieved a perfect restoration of foot viability in the replanted foot. The patient was allowed to walk independently at 6 months postoperatively, demonstrating sufficient power of ankle motion. The ankle flexion and extension were adequate in the replanted foot. Despite visible calf muscle atrophy and trophic changes in the replanted foot, the patient expressed his satisfaction with the foot and had no further complaints, such as cold intolerance (Fig. 3). He was able to return to his school and previous job and was able to walk with noticeable limping (Supplemental Digital Content, Video 1, http://links.lww.com/SAP/B23).

Video 1. Walking of the patient at 10-year follow-up. No limping or difficulty is observed during daily walking activities.

Sensory function started to restore nearly 3 months after the nerve grafting. Two-point discrimination was 4 to 6 mm on the plantar side of the replanted foot. On the dorsal side, there was no detectible sensation. Light touch sensation by Semmes-Weinstein monofilament testing was within normal limits. No ulcerations and skin breakdown were observed during the 10-year follow-up.

Gait Analysis

Dynamic podography showed normal pressure distribution on the plantar surface of the replanted foot. Cadence, walking speed, and dual-step length were close to normal. On the left, step length and duration were longer than on the right, whereas the single support phase was

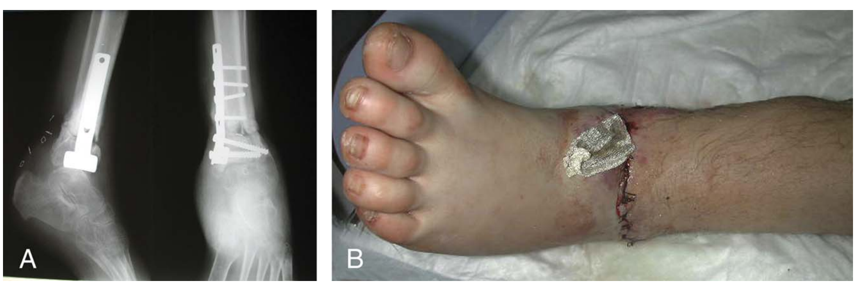

FIGURE 2. A, AP/L x-ray image of the replanted foot. B, Immediate postoperative appearance of the replanted foot.

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FIGURE 3. Late postoperative appearance. Left panel shows the appearance during walking. Right panel shows the weight bearing of the replanted foot. Please note the trophic changes at the skin, flexion contractures of the toes, and calf atrophy (arrow).

observed to be shorter on the left. A comparison of the main gait parameters between the injured and uninjured foot is depicted in Table 1.

Ankle Kinematics

The first contact (initial contact) on the sagittal plane was observed when the right ankle dorsiflexion was 15 degrees, whereas the left ankle was at 20 degrees of plantar flexion. At the end of the phase, the right ankle showed 4 degrees of plantar flexion, whereas the left ankle showed 10 degrees of plantar flexion in the middle of the pressing phase, and increasing to 15 degrees of plantar flexion at the end. During the oscillation phase, the right foot dorsiflexed up to 15 degrees, whereas the left foot remained in plantar flexion until 15 degrees.

Knee Kinematics

During the initial contact, knee kinematics showed a flexion angle of 10 degrees on the left and neutral on the right. In the stance phase, the maximum knee flexion was 10 degrees on the left, whereas the right knee remained at 10 degrees extension. This situation may be a result of the angular data of his ankle (left ankle in plantar flexion, while right ankle stayed in dorsiflexion). During the oscillation phase, the maximum knee flexion was 55 degrees in both knees.

TABLE 1. Comparison of Main Gait Analysis Parameters in Injured (Right) and Noninjured (Left) Foot

Parameters	Left	Right
Cadence (steps/min)	90.8	93.8
Double support (s)	0.40	0.36
Single support (s)	0.38	0.54
Step length (m)	0.62	0.54
Step time (s)	0.76	0.56
Stride length (m)	1.15	1.11
Stride time (s)	1.32	1.28
Walking speed (m/s)	0.87	0.87

Hip Kinematics

At the initial contact of both hips, the right hip was flexed at 35 degrees, and the left hip at 25 degrees. At the end of the pressing phase, both the right and left hips exhibited 10 degrees of flexion. Additionally, an anterior pelvic tilt of 10 degrees was observed, whereas the rotation data and pelvic obliquity were close to neutral.

DISCUSSION

The choice between amputation and limb replantation has always been challenging. Although effective functional lower limb restoration can be achieved through prosthetics, recent advancements in microsurgical techniques have led to a greater focus on enhancing functionality through limb salvage.[8,11,21] The patient's age, comorbidities, ischemia time, type of injury, and side of injury (unilateral or bilateral) are determinants in the decision making process between replantation and primary amputation.[8,10,22] Additionally, psychosocial factors related to the injury and rehabilitation must be taken into consideration. To achieve a successful replantation, patients should be evaluated in the light of these general guidelines. Battiston et al developed a scoring system to facilitate the decision making process for lower limb replantation.[21] According to this scoring system, our case was categorized as "possible replantation, poor functional result." However, our functional results were good. We believe that one of the major determinants for positive outcomes in our case, despite severe tissue injury, is the level of injury, which was close to the ankle without damage to the joint. Thus, there is a need for updated scoring systems, especially including the level of the injury and joint involvement as parameters.

Given the advancements in microsurgical techniques, the viability of the limb after replantation is no longer considered sufficient for satisfaction and success.[8,9] The functional, esthetic, and socioeconomic aspects of outcomes in replantation should be taken into consideration.[1–7] There are only a small number of studies that are focused on the objective functional outcomes of lower extremity replantation, especially in the long term.[1,23] The classification by Chen is globally used to evaluate lower extremity function.[1] Our case was able to return to the levels of previous work with a normal gait and almost normal ROM of knee and ankle joints, making it Grade I according to Chen classification. However, this classification may also need refinements as it was originally described in the 1980s with many advances since. Especially, a scoring system based

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on the return to work, walking, sensibility, and range of motion at certain joints would be helpful for better standardizing long-term functional outcomes.

Visual inspection of gait has limited value as it lacks quantitative information and is limited by rapid and complex nature of human locomotion. Additionally, it is challenging to perceive gait deviations and compensations in the walking patterns of individuals with lower limb reconstruction. Gait analysis is gaining clinical interest and importance in evaluating the functional outcomes after lower extremity reconstruction, and it is correlated with patient's functional outcome after surgery.[11,15,16,24,25] Gait analysis of our patient demonstrated similar angular ankle movement patterns during all phases of the gait, except the oscillation phase where the leg swung forward and not in contact with the ground. During this phase, although the replanted foot was in dorsiflexion, the normal foot remained in plantar flexion. As this abnormal gait pattern occurred during oscillation phase, it enabled the patient to walk without visible limping. However, we believe that the reason for dorsiflexion of the right ankle during this phase may be due to weakness and/or fibrosis of the gastrocnemius and soleus muscles, secondary to avulsion that occurred at the initial injury. The hip and knee kinematics showed that, despite no injury occurring in these areas, the patient developed a compensatory gait. This compensation was more pronounced at the knee joint than at the hip joint. Ankle joint kinematics did not exhibit significant differences in both ankles; however, we believe that ankle problems with increasing severity could lead to more notable compensations in the knee and hip joints. This type of abnormal gait patterns is expected after major lower limb surgeries, which is known as gait compensation.[26] Although this compensation in our patient is not very significant, the long-term effects of compensatory gait might be significant such as early and more severe osteoarthritis development.[27] One limitation of our gait analysis is that we do not have early gait analysis to compare the evolution of the gait of the patient and determine the progression of the compensatory mechanisms, which might be helpful in better understanding the postoperative period of lower limb replantation.

The length discrepancy between the 2 limbs in our patient was 5 cm. Although the literature suggests that discrepancies above 2 cm can lead to an increased metabolic cost of ambulation and abnormal gait, we did not observe major issues such as pelvic drop or compensatory flexion to shorten the long limb.[28,29] We believe that the young age of our patient might have contributed to this positive outcome. In addition to better regeneration, this could be another advantage of replantation in younger patients.

Finally, sensation in the replanted foot stands as one of the most crucial factors influencing durability and long-term success. Ensuring at least protective sensation at plantar surface of the foot is essential for a successful foot replantation. Therefore, the repair of the posterior tibial nerve holds utmost importance. Nerve regeneration relies on a supportive environment for improved outcomes. We believe that secondary nerve grafting is a viable option to facilitate better nerve regeneration, unless the amputation is a clear-cut guillotine type injury.

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