Total Ankle Replacement in a Military Jet Pilot

Paola Verde; Stefano Guardigli; Fabio Morgagni; Steve Roberts; Donato Monopoli; Andrea Scala

INTRODUCTION: A total ankle replacement in a jet pilot after an open, high-energy foot and ankle fracture and dislocation with talar extrusion in a plane crash was carefully evaluated before considering fitness to fly.

CASE REPORT: A 33-yr-old male test pilot of the Italian Air Force was involved in a plane crash and reported an open high-energy fracture/dislocation of the right ankle, with the expulsion of the right talus due to the impact, and other fractures. A titanium replica was inserted inside the ankle. However, the patient suffered from intolerable pain and developed arthritic changes in the cartilage of the tibial plafond. For these reasons, a decision was made to perform a custom-made total ankle replacement.

DISCUSSION: The 2-yr follow-up after the last operation and the evaluation of the pilot's fitness to fly are reported in this case study. The pilot was assessed fit to fly, including high performance military aircrafts.

KEYWORDS: total ankle replacement, talus expulsion, fitness to fly, air crash.

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Impacts and decelerations associated with aircraft crashes are relatively frequent sources of severe traumatic injuries, as previously discussed in the literature.[14,17] Among the most frequent forms of trauma seen in aircraft crashes are fractures and associated soft tissue injuries of the lower extremities.[8] Generally, the applications of these forces can be dramatic, especially in crashes with the highest impact velocities or shortest deceleration distances. Coltart[1] described "aviator's astragalus," fractures of the talar neck, in pilots of aircraft with toebrakes.

In our case, an expert test pilot on duty was involved in a near fatal accident, suffering several open fractures, including the extrusion of the right talus. Two major surgeries were required on his right ankle. The first, 2 mo after the event, included the insertion of a titanium replica of the lost talus, but was unsuccessful, and then a total ankle replacement was carried out 2 yr after the event using an innovative implant. The replica of the right talus, in fact, was made with Ti6AI4V alloy and manufactured by electron beam melting. A 3D technology used the CT scan of the patient's left ankle as a template. The model had metal trabecular structures capable of matching some of the mechanical properties of human bone. To complete the implant, a mobile inlay of 6 mm of ultra-high molecular weight polyetilene (UHMWPE) was inserted to restore at least 40° of ankle range of motion.

In order to reassess fitness to fly after such a plane crash, careful aeromedical considerations were made, taking into account the extraordinary environment of the military flight, the forces involved in different aircrafts in different conditions, the occupational hazards, and also the pilot's response. Surgical intervention, post op, and aeromedical evaluation are described here.

CASE REPORT

A 33-yr-old male Italian Air Force test pilot was involved in a plane crash. The patient was sitting as a passenger on the right seat of a Dyn Aero MCR 180R. This light aircraft, designed to tow motor gliders, has two side-to-side seats and the company

From the Flight Experimental Centre, Pratica di Mare AFB, Pomezia, Rome, Italy; the Institute of Aerospace Medicine, Rome, Italy; Martin-Baker, Uxbridge, United Kingdom; the Instituto Tecnologico de Canarias, Las Palmas, Spain; and the Ars Medica Clinic, Rome, Italy.

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Address correspondence to: Lt. Col. Paola Verde, M.D., Ph.D., ItAF Aerospace Medicine Department, Flight Experimental Centre, Pratica di Mare AFB, 00071 Pomezia, Rome, Italy; paola.verde@aeronautica.difesa.it.

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pilot was sitting on the left side. During a recognition flight and pre-launch weather evaluation by means of a glider Winch-launching system, the aircraft was subject to excessive loss of altitude due to loss of control by the pilot in command, who was incapacitated following an encounter with sudden rain and critical weather conditions. Presumably he suffered from a type of disorientation, being "frozen" on the stick. The injured person for this case report was the test pilot seated on the right side. The pilot on the right side took control of the airplane and attempted to recover from this unusual attitude, but the aircraft impacted the ground at about 120 km/h, hitting a cement draining line in a grass field with the main landing gear. The crash resulted in the aircraft breaking up into three main parts: the cockpit, the nose, and the tail section. The subject on the left side was basically unharmed and remained inside the cockpit, while the pilot on the right side, the injured person for this case report, was ejected outside, still attached to the backrest of the seat, and suffered severe injuries of the right leg.

The patient was transferred to a trauma center and underwent radiographic examination that showed an open fracture/dislocation due to high-energy trauma of the right ankle with extrusion of the right talus, together with fractures of the proximal plateau of the right tibia and diaphysis of the 4^{th} and 5^{th} metatarsal bones and left proximal phalanx of the first toe, along with fractures of the right ulna. After appropriate cleaning and debridement, the right ankle joint was filled with a bone cement spacer and temporarily stabilized with an external fixator. The proximal fractures of the right tibia and metatarsal bones were treated with open reduction internal fixation.

The orthopedic surgeons of the trauma center decided to perform a metallic replacement of the missing talus. A CT scan of the uninjured left ankle was sent to the Canary Islands Institute of Technology. A titanium right talus was made by means of a 3D printing technology using the CT scan of the patient's left ankle as a template.

The patient underwent the implant of the talus 2 mo after the accident. The deltoid ligament and the anteromedial capsule of the ankle were reconstructed with a cadaver tendon. The tendon was attached to the frontal aspect of the distal tibia (on the antero-medial area) using an AO screw locking fastener for ligaments. The anterior talar fibular ligament and the lateral part of the joint were reconstructed with a cadaver tendon. Proximally, the cadaver lateral tendon was inserted and anchored into a tunnel dug into the fibular malleolus.

At the end of the procedure the titanium talus was placed in the ankle joint, but was in direct contact with the cartilage of the tibial plafond. A plaster cast was placed from the groin to the toes in order to immobilize the operated right lower limb. The patient wore the plaster cast for a month. After removal, weight bearing was forbidden for 2 mo to allow the healing of the proximal epiphysis fracture of the tibia and the medial and lateral ligament reconstruction.

The patient was allowed to walk using two crutches 3 mo after surgery. Nevertheless it was impossible for the patient to resume ambulation, as he suffered from severe pain. The radiography of the right ankle showed a reduction of the articular space due to cartilage absorption, in particular on the medial side, 1 yr after the operation.

The ankle range of movement (ROM) was blocked at 30° based on 80° dorsiflexion and 110° plantar flexion. The Achilles tendon was retracted. There were no prono-supination or inversion-eversion movements since the subtalar joint was blocked by two screws at the posterior talus-calcaneal joint. At the level of the right talo-navicular joint the titanium talus was directly in contact with the cartilage surface of the navicular (**Fig. 1** and **Fig. 2**).

A total ankle replacement was performed 2 yr after the first intervention. A CT scan of the left ankle was sent to the Canary Islands Institute of Technology with two specific requests:

- manufacture of a custom made tibial component adapted to the conformation of the patient's right distal tibial plafond. The tibial component had to take into account the bone tunnel left by the removal of the AO screw locking fastener ligaments; and
- manufacture of a high-density polyethylene component to be adapted to the surface of the talus and the surface of the tibial component.

The Canary Islands Institute of Technology performed a 3D rendering and then made the implant in titanium type Ti6Al4V manufactured by electron beam melting (EBM ARCAM S12, Arcam AB, Mölndal, Sweden), a 3D manufacturing process of proven effectiveness for orthopedic implants.[5,6,12]

The tibial implant had a flat dense mirror polished surface suitable for mobile polietilene inlay and a highly porous, fully interconnected, anisotropic gyroide structure in contact with the spongy bone of the distal tibial epiphysis.[4] The mobile inlay was made up with UHMWPE. It had a flat upper part perpendicular to the load bearing direction in contact with the metallic tibial component and a biconcave lower part congruent with the previously implanted titanium talus replacement. The planned thickness of the UHMWPE was 6 mm to assure a correct ligament tension and avoid ligament looseness, which is harmful for ankle stability while weight bearing.

During surgery, the articular cartilage of the right ankle appeared to be thinned, hyperemic, and completely reabsorbed. The tibial plafond subchondral bone was almost completely exposed. There was no ROM of the ankle joint. The cutting "template" was applied to the anterior aspect of the distal tibial plafond and the appropriate amount of bone was resected. The custom-made tibial component was implanted and adapted to the conformation of the distal epiphysis of the patient's tibia. The mobile polyethylene inlay (6 mm) was inserted between the tibial and talus surface (**Fig. 3** and **Fig. 4**). The lengthening of the Achilles tendon was performed by a percutaneous technique.

Post-operative day 1. Continuous passive motion (CPM) of the operated right ankle was started after the operation in order to prevent articular stiffness and was scheduled for 2 mo. Four to five passive mobilization sessions of 20 min each were performed on a daily basis. The patient was allowed to walk with partial weight bearing, with crutches, four to five times a day.

Fig. 1. Pre-op total ankle replacement: frontal view. The X-ray of the ankle in frontal view shows the metal talus in contact with the tibial plafond. There is no articular space. This finding explains reabsorption of the articular cartilage, the ankle ankylosis, the impossibility of walking, and the severe pain. The screw and the washer with spikes for ligament reconstruction on the distal tibia should be noted, as well as the tunnel on the fibular malleolus.

Fig. 2. Pre-op total ankle replacement: lateral view. The X-ray in lateral view shows the disappearance of the ankle joint space. The metallic talus is in contact with the tibial plafond. The reabsorption of articular cartilage is apparent.

The duration of the ambulation was 10–15 min. The patient was dismissed on postop day 3.

Post-operative day 7. The patient was allowed to walk with partial weight bearing with crutches four to five times a day. The duration of the ambulation was 10–15 min.

Post-operative day 15. The CPM program continued, as well as walking with crutches.

Post-operative month 1. The CPM program continued. The patient began to wear regular sneakers and was allowed to go out for short walks. He started driving the car again. He abandoned the use of crutches after 3 mo.

Post-operative month 6. The patient wore plantar orthotics to compensate for the supination of the forefoot, secondary to the talo-navicular impingement. He started a master's course for his military career advancement.

Post-operative year 1. After total ankle replacement, the pilot was judged fit to flight (no ejection seat aircrafts).

Post-operative year 2. After careful aeromedical evaluation, the pilot obtained his fitness to fly on high performance jet aircrafts.

DISCUSSION

Surgical Considerations

Total ankle arthroplasty has been in development for more than 40 yr. Although early designs were experimental with high failure rates, current implants are significantly improved, showing improved functional results and clinical outcomes. Total ankle replacement designs are split into mobile-bearing and fixed-bearing designs. When deciding whether to perform ankle arthroplasty, many factors need to be considered to determine if the patient is suitable and which implant is their best fit.[10]

Until a few years ago, arthrodesis was the only option to overcome end-stage ankle arthritis. The joint was fused to prevent motion and thus eliminate the pain caused by the motion. However, over time the adjacent joints are forced to increase motion in order to accommodate ambulation and they experience increased forces. This leads to rapid joint deterioration with subsequent increased pain and stiffness. The result is lower quality of ambulation and function.[16]

Fig. 3. Post-op total ankle replacement: frontal view. The postoperative frontal view radiograph of the ankle joint replacement shows the volume of the tibial implant and the alveolar shape. It was designed to fill the hole left in the distal tibia by the removal of the screw and ligament washer for ligament reconstruction. The polyethylene inlay has restored the joint space. The range of motion of the ankle is quite normal and the pain is absent or tolerable.

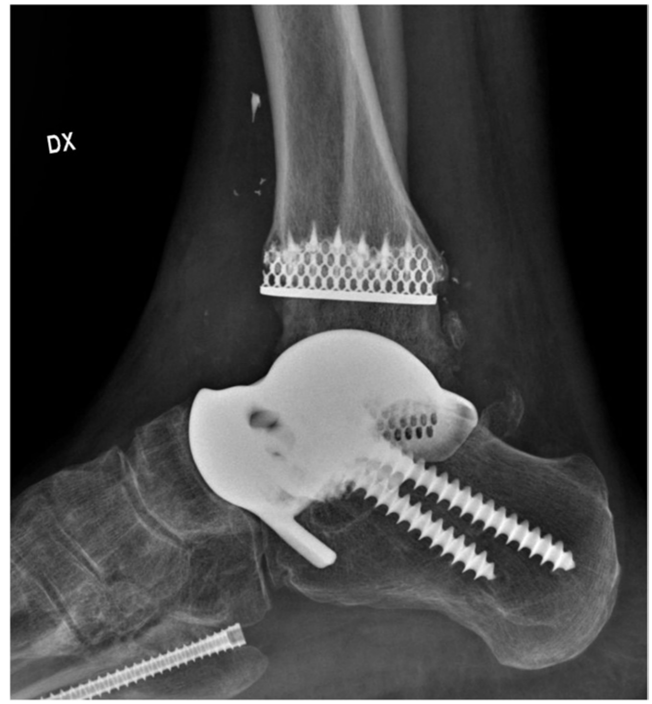

Fig. 4. Post-op total ankle replacement: lateral view. The postoperative lateral view radiograph of the ankle joint replacement shows the tibial component with its alveolar structure. The polyethylene inlay has restored the joint space.

In our case a mobile-bearing design was decided on after the failure of a previous tibio-talar arthroplasty in which a total talar prosthesis replacement was carried out after talar extrusion. The decision was driven by the young age of the patient and by his expectation of returning to fly.

Metallic custom-made replacements are commonly used in bone reconstruction surgery and titanium appears to be the metal of choice due to its features: lightness, elasticity, and resistance, with less oxidative process and free radical formation.[3] Indeed, the tibial implant used here was made with Ti6A4V and manufactured by electron beam melting (EBM Arcam S12). Ti6A4V, in fact, has a gyroide structure that is effectively able to promote bone regeneration in large bone defects.[13] It shows good osteoconductivity, meaning that it is highly biocompatible as bone can grow on its surface.[6] It also presents reduced formation (by 30%) of bacterial biofilm (*Staphylococcus aureus*) per unitary surface of porous structures, compared to flat structures, also manufactured by EBM.[7] This highly porous gyroide structure had been selected among several different alternatives due to the beneficial mechanical properties exhibited under compression and torsional loads.[2,18]

Finally, the natural healing capacity of bone can be enhanced by the biomechanical properties of the trabecular implant in which mechanical loading is essential for maintaining and regulating bone mass.[9,11] The mobile polyetilene inlay (UHMWPE), already known in standard ankle replacement, has in this case a 6-mm thickness to satisfy the requirement of restoring at least 40° of ankle ROM movement to resume flight activity.

Operational Considerations

Nevertheless, in operational aviation medicine, several issues come into play when a jet pilot with a successful total ankle replacement has to be judged fit to fly. Main observations are as follows.

Ingress/egress. Ingress and egress in a conventional propeller or jet-engine transport airplane does not require any particular angular foot movement. Cockpits are always large enough and dedicated ladders are always provided to access and exit the cockpits in a comfortable way. The pilot involved in the aforementioned crash was initially medically cleared to fly these types of airplanes and was also involved in a collapse of a main landing gear of a Piaggio P180 Avanti airplane and executed an emergency ground egress with no issues using the main retractable ladder/door installed on the airplane. At the same time, ingress in a fighter cockpit is not an issue since dedicated ladders or retractable steps are provided to aid pilot entrance. For the same reasons, egress from a cockpit during normal operation-shutdown does not require any particular effort for the pilot. However, an emergency ground egress procedure in a jet fighter airplane requires the pilot to leave the cockpit in the quickest and safest way, without any external aid (i.e., maintenance ladder, excluding the onboard ladder installed in the airplane, i.e., Eurofighter Typhoon and F-35). Usually, the most used technique to abandon a jet airplane with an excessive cockpit height from the ground is to walk on the wing and either step down on the wing tank or slowly slide down facing the wing leading edge, thus avoiding a jump from an excessive height. However, the aforementioned procedure really differs from aircraft to aircraft. Indeed, pilots perform adequate training to ensure they find the best technique to leave any airplane while keeping the risk of possible injuries due to fall to a minimum. It is also important to remember that the pilot is carrying extra weight due to the equipment needed in a high performance jet: this is about 10 kg on average, which will increase the load on the lower part of the body during ground impact if jumping from the cockpit area/wing of the airplane is required. Moreover, a test pilot, as in this case, is away from any form of so called "scramble" procedures where the pilot is required to reach the airplane in a very short time (i.e., minutes) in order to take off to intercept a possible aerial threat.

Rudder pedal operation and relative forces (high performance jet aircraft vs. conventional a/c). The biggest issue faced by the pilot was to get used to the heavy pedal forces required when using the rudder pedals when flying dual engine conventional airplanes. The training for this aircraft's category requires the pilot to perform simulated engine failures during critical phases of flights (i.e., after takeoff rotation and on final for landing), where asymmetrical forces created by the remaining engine result in an excessive opposite yaw moment, which has to be countered immediately by the pilot in order to avoid losing aircraft control. Similar issues are also encountered when flying in a heavy crosswind, where the pilot keeps the nose of the aircraft aligned with the runway by using the rudder pedals while opposing the wing-up moment caused by the crosswind with the yoke.

According to the different aircraft specifications, as reported in **Table I** by the flying engineers, in a conventional dual-engine airplane, the loads required to reach full pedal travel in a worst-case scenario (one failed engine and opposite engine at full thrust) are 2 to 3 times higher compared to the forces required on a jet fighter airplane. In fact, in the fighter case, the rudder pedals' design purpose is to allow the pilot to taxi the airplane on the ground while ensuring an adequate control margin in the yaw axis in order to permit alignment of the nose of the aircraft with the runway heading in the presence of heavy crosswinds during the landing phase. Furthermore, in jet fighter planes the flight control computer and fly-by-wire technology are controlling most of the control surfaces' movements as a

Table I. Aircraft Specifications.

				MAXIMUM RUDDER PEDAL FORCE	
AIRCRAFT	CATEGORY	NOTES	APPLICABLE REFERENCE	ACCORDING TO THE OFFICIAL REFERENCES	MEASURED DURING FLIGHT TEST
Aermacchi M-346 (dual engine fighter jet)	Class IV (MIL8785)	Fly-by-wire control system pedals with artificial sensitivity spring.	MIL Specs 8785C/1797A	§3.3.7 Max pedal force for 90° crosswind < 45 kg.	Taxi/ground roll: at 50–60 kt with 25-kt crosswind, one engine inoperative without use of the nose when steering: almost full pedal deflection was required to counteract the yawing moment with a pedal force of 35 kg. Landing phase with 25-kt crosswind: < 75% pedal deflection required with a pedal force of 26 kg.
ATR-72 (dual engine prop transport)	Class III Category B	Mechanical link from rudder to rudder pedals in the cockpit (spring-tab installed).	CS-25	At full rudder or pedal force up to 180 lb (82 kg), the pedal force may not reverse and increases in rudder deflection must produce increased angles of sideslip.	Max pedal force experienced was about 105 kg (231 lb) at about 85% of full pedal travel.
C-27J (dual engine prop transport)	Class III Category B	Mechanical link from rudder to rudder pedals in the cockpit with hydraulic booster and an artificial sensitivity spring installed.	CS-25	At full rudder or pedal force up to 180 lb (82 kg), the pedal force may not reverse and increases in rudder deflection must produce increased angles of sideslip.	Max pedal force experienced was 59 kg (130 lb) with full pedal at minimum control speed.

result of what the pilot asked the airplane to do by actuation of control stick and pedals. This allows the system to avoid entering a critical flight condition (>9 G protection, excessive yaw rates and angles) which could lead to loss of aircraft control. Rudder pedals are then used in a less extensive way compared to a conventional multiengine aircraft.

Ejection seat. Among the issues to consider for pilot safety after a total ankle replacement is the probability of ejection and the theoretical injury risk for parachute landing fall (PLF). According to Martin-Baker,[15] in order to reduce the risk of a leg injury caused by PLF to a level of 5% per parachute jump, the ejection seat parachute resultant velocity must be limited to a maximum of 9.1 $m \cdot s^{-1}$, the vertical descent velocity to less than 7.31 $m \cdot s^{-1}$, with a steady state maximum horizontal velocity of 3.04 $m \cdot s^{-1}$, for no-wind conditions at sea level, across the full range of aircrew boarding masses. The Martin-Baker IGQ5000 parachute fitted to the IT10A seat (Tornado), IT16D seat (M346), and Mk16A seat (Typhoon) will achieve this for all suspended weights (dressed mass, harness, and SSK) up to 132 kg, while the IGQ6000 parachute fitted to the US16E seat (F-35A/B) will achieve this for all suspended weights up to 153 kg.

The acceptable PLF leg injury rate is, therefore, conservatively set at 2×10^{-2} per parachute jump when the Martin-Baker parachutes have a much lower descent velocity than the PLF risk suggests. Martin-Baker has historically used a conservative ejection rate of 5×10^{-5} per flight hour for prototype/developmental aircraft, while the U.S. Air Force has recorded a rate of 9.6×10^{-6} ejections per flight hour across a 10-yr average (2007–2016).

This means that the probability of a PLF injury per ejection/flight hour is calculated as follows for any ejectee: 9.6×10^{-6} ejections per flight hour $\times$ 2×10^{-2} injuries per parachute jump $= 1.92 \times 10^{-7}$ PLF injuries per ejection/flight hour. In practical terms this means that for every 1 million flight hours, 10 pilots will eject. When we consider 2 injuries for each 100 ejections, 2 leg injuries will happen in only 10 million flight hours. The U.S. Army research into paratrooper PLF injuries also looked at the effects of gender, obesity, activity, and health. They concluded that young men with a low body mass index who are aerobically fit and physically active carry the lowest risk of PLF injury.

Aeromedical Disposition

In terms of fitness to fly the disposition followed the pilot's functional recovery and his ability to safely operate the aircraft. The pilot was employed as a test pilot at the time of the accident. He held different type ratings on many rotary and fixed wing aircraft. For this reason, the case was also discussed from the perspective of saving the investment made in the pilot's training. After the last operation the pilot recovered complete capability to walk, exercise, and he was able to pass the mandatory military fitness test, which also includes a 2-km run in 14 min.

Three elements of concern were considered from an operational point of view. First, the ability to apply the right force on the pedals, mainly during movement on the ground and during roll. Special considerations were made on controlling the brakes with the pedals on different aircrafts. Second, the ability to ingress and egress from the aircraft, including an emergency egression, was considered. Special considerations were made taking into account different aircrafts and helicopters because of the pilot's multiple qualifications. Third, the risk of injury related to emergency ejection and parachute landing was considered.

Due to all these considerations, after the first operation the pilot was declared temporarily unfit as the ankle was blocked and weight bearing was very painful. At that time, due to the ankle block, the severe functional impairment, and pain, the pilot was informed that a fit assessment would have been impossible. However, given the strong attitude of the pilot to continue the rehabilitation process, he was encouraged by the medical team to go ahead on the program and another surgeon was consulted in order to evaluate a strategy to fix the pilot's problems.

After the second operation the pilot recovered good functional capability and sufficient freedom of movement of the ankle so that he was able to push the pedals appropriately. All information provided by the manufacturing companies of different aircrafts in terms of forces needed to operate the rudder pedals in different conditions were compared with pilot strength testing obtained by means of a myometer to assess muscles strength.

A set of tests demonstrated that the pilot was able to ingress and egress safely from different aircrafts. The demonstration of his capability to control the pedals safely and to perform the emergency procedures appropriately lead the Institute of Aerospace Medicine to issue a fit to fly certification on conventional aircrafts. Finally, 2 yr after the second surgery, after having collected a robust set of data about the dynamics of landing with a parachute during an assisted escape, the risk for flight safety and the risk for the pilot's health were assessed as being acceptable and the pilot was declared fit to fly without limitations.

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Authors and affiliations: Paola Verde, M.D., Ph.D., and Stefano Guardigli, M.Sc., Flight Experimental Centre, Pratica di Mare AFB, Pomezia, Rome, Italy; Fabio Morgagni, M.D., Institute of Aerospace Medicine, Rome, Italy; Steve Roberts, M.Sc., Martin-Baker, Uxbridge, United Kingdom; Donato Monopoli, M.Sc., Instituto Tecnologico de Canarias, Las Palmas, Spain; and Andrea Scala, M.D., Orthop. Surg., Ars Medica Clinic, Rome, Italy.

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