Istituto di Tecnologie Industriali e Automazione
Consiglio Nazionale delle Ricerche

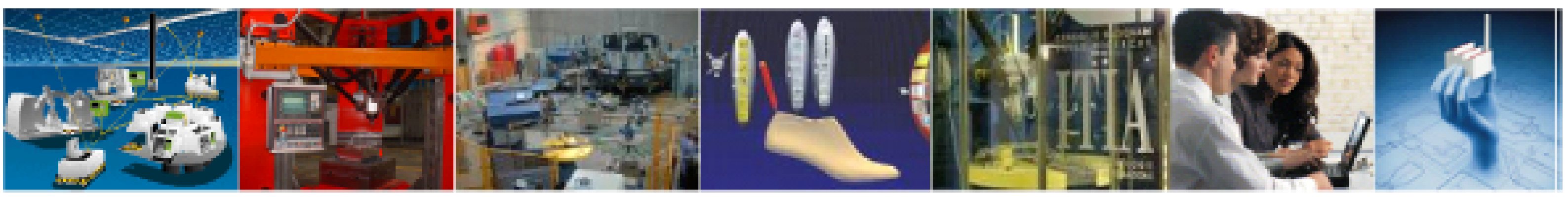
Short term mobility 2011 report

Matteo Malosio, CNR-ITIA

CNR-ITIA – Technical Report Series

Technical Report No.
ITIA/TR/2011-001

September 2011



CNR-ITIA – Technical Report Series

Published by:
CNR-ITIA, *Consiglio Nazionale delle Ricerche*
Istituto di Tecnologie Industriali e Automazione
via Bassini 15
20133 Milan, Italy

Technical Report no. ITIA/TR/2011-001

Revision history:
ITIA/TR/2011-001.001 September 2011

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Short term mobility 2011 report

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1 Introduction

A number of studies have proved the efficacy of robotics in neuromotor rehabilitation [1, 2, 3], but the intrinsic field complexity is a cause of the great number of more and more complex devices continuously being developed, in order to satisfy as much as possible rehabilitation therapies requisites.

The interest in developing devices able to interact with the patient is continuously growing. The must guarantee that the movement of the muscular-skeletal apparatus is as much as possible compatible with the physiological movements of articulations and human limbs, allowing a great coverage of the functional range-of-motion of human articulations, compatibly with actual movements performed by the human body. Neuromuscular rehabilitation of foot articulations is particularly important for the fundamental role that they play in allowing the patient to recover his own autonomous mobility.

The device currently being developed by CNR-ITIA, in the Robotics Rehabilitation Lab, is a rehabilitation biomedical device for the rehabilitation of the human ankle named *PKAnkle*. In this document, after a presentation of medical requirements (Section 2) and a review of so far developed state-of-the-art ankle rehabilitation devices (Section 3), the prototype *PKAnkle* is presented in Section 4, highlighting kinematic characteristics, optimization parameters and mechanical design results. In Section 5 conclusions and future plans are presented and an improved version of the kinematic scheme is illustrated for future developments.

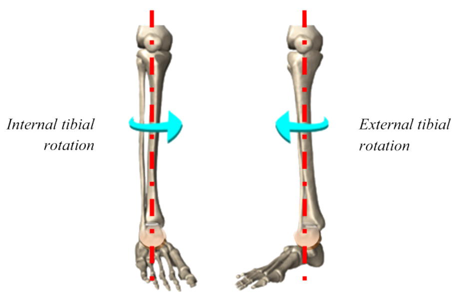
2 Application requirements

The device for ankle rehabilitation has to allow a correct mobilization of the articulations which produces the actual foot movements. For this reason a small introduction about anatomical aspects is presented in this section. Afterwards, the influence of the position of the ground constraint of the device on ankle rehabilitation mechanism and exchanged force/torque is presented.

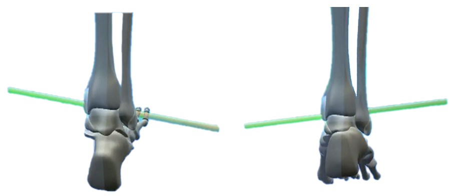
2.1 Anatomical aspects

Three distinct movements characterize the foot/ankle articulation and are hereafter introduced.

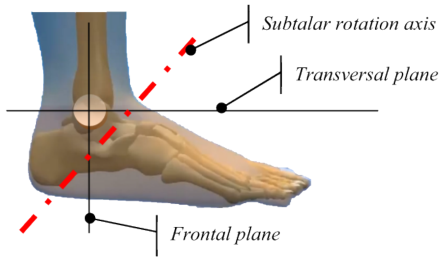
Internal/External tibial rotation
Kinematically equivalent to a revolute joint with the rotational axis passing through knee and ankle centers



Tibiotarsal dorsi-plantarflexion
Usually known as the ankle articulation, placed between the tibia and the fibula, and the talo, representable with a rotation around the axis normal to the sagittal plane and passing through the medial and lateral malleolus. Actually the axis of the rotational joint is oscillating, as function of the dorsi-plantarflexion angle. In the figure on the right the direction of the axis of rotation is shown, in complete foot flexion (left) and extension (right).



Subtalar inversion/eversion
A rotational axis is positioned between the talo and the foot allowing a rotation of the foot around an axis belonging to the sagittal plane, oriented approximately as the bisector of frontal and transverse planes.



From a functional and anatomic point of view rotational axes do not perfectly intersect themselves [4], but the distance between them can be ignored for rehabilitation aims. The ideal center of rotation of the ankle can be consequently approximated by the midpoint of the shorter segment between these axes, in the talo medial part, as represented in Fig. 1.

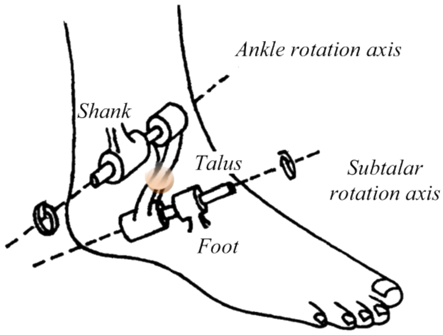


Figure 1: Ankle and subtalar rotation axes.

2.2 Effects of device constraint position

Positioning the platform center of rotation nearby the center of rotation of the ankle let the device, and the patient, to act on articulations and muscles in a focalized manner, limiting possible compensatory movements which can typically happen during the therapy for patients with limited motor functionalities. Functional relapses of the constraint relative position are illustrated in Fig. 2.

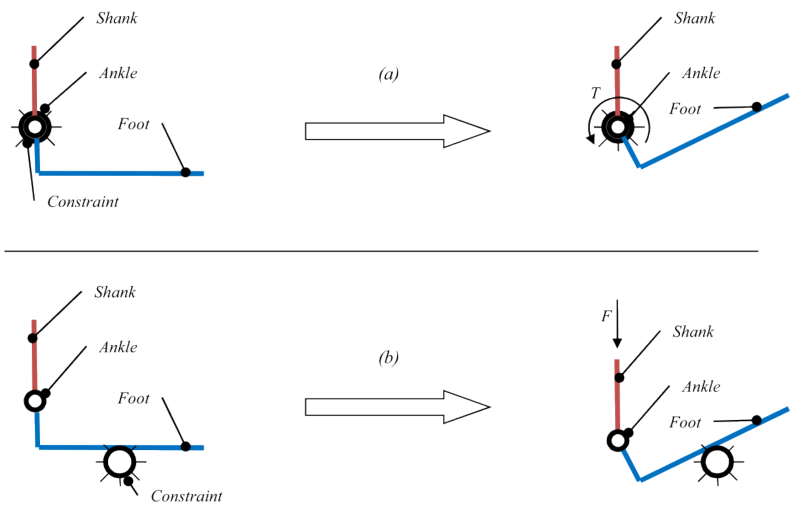


Figure 2: Effects of external constraints position with respect to ankle joint position.

If the foot is constrained nearby the actual ankle center of rotation, the patient can perform ankle flexional movements only exerting a torque around the ankle rotational axis (Fig. 2a).

If the foot constraint is not coincident with the center of the ankle (*e.g.*below the foot arch, as represented in Fig. 2b), the patient action can result in an ankle dorsi-flexional movement exerting a force along the tibial axis (*e.g.*by the biceps femoris contraction on a sitting position), instead of a torque around the ankle axis. In other words, the patient can be able to perform a "correct" movement exploiting the action of "wrong" muscles.

The aim of *PKAnkle*, with the creation of a purely rotational platform centered in the ankle center, is consequently considered particularly interesting for the patient recovery from a functional point of view.

3 State of the art

In this section a review of state-of-the-art robotic device for ankle rehabilitation is presented, highlighting drawbacks and aspects to be improved. These aspects have been taken into consideration in conceiving and designing *PKAnkle*, as reported in Section 4.

3.1 Parallel type multi-freedom artificial limb exoskeleton ankle joint

The device [5] is characterized by three parallel degrees of freedom, but joints and links dispositions do not determine three degrees of freedom associable to actual ankle movements. In fact, the vertical translational movement along the platform z axis, obtained by a synchronous actuation of the three axes, does not correspond to a physiological ankle movement. Moreover, the necessity for the patient to "wear" and constraint the device to the lower part of the lower limb can be hardly used by a number of patients, not able to support the weight of the device.

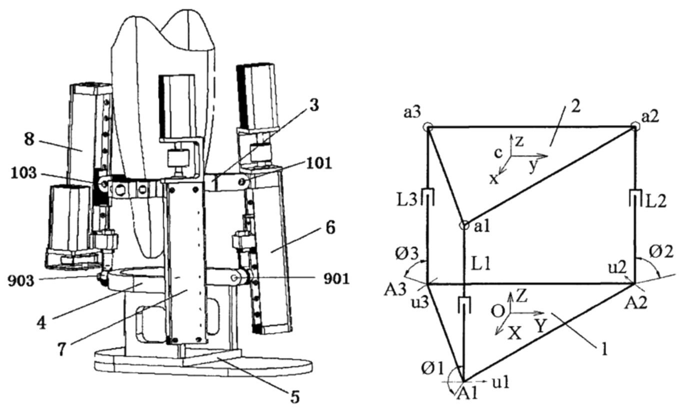


Figure 3: Parallel type multi-freedom artificial limb exoskeleton ankle joint.

3.2 Ankle rehabilitation device

This device [6] is characterized by two degrees of freedoms. For a correct actuation of the device it requires to be constrained to the lower part of the lower limb. This solution can be not easily applicable due to the presence of soft tissues of patient's body. It is in fact quite hard to apply an orthosis along the axial direction of a limb, *i.e.*along the bone, because of the relative shift between the skin and the bone of the human body, without applying high constraining forces between the orthosis and the human body. The position and alignment of actuators can produce internal ankle forces, not directly related to actual ankle movements.

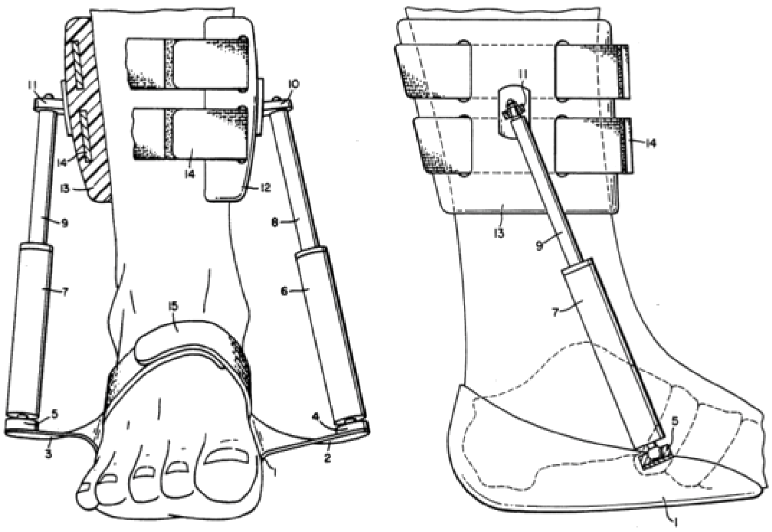


Figure 4: Wearable ankle rehabilitation device.

3.3 A High-performance Redundantly Actuated Parallel Mechanism for Ankle Rehabilitation

The redundant device [7] is characterized by three actuators. The two main disadvantages of this device, faced designing *PKAnkle*, are:

- linear actuators cause the device to be high and hardly positionable for the use by a seated patient;
- the position of the center of rotation below the foot, and not nearby the actual center of rotation of the ankle, can have disadvantages highlighted in Section 2.2.

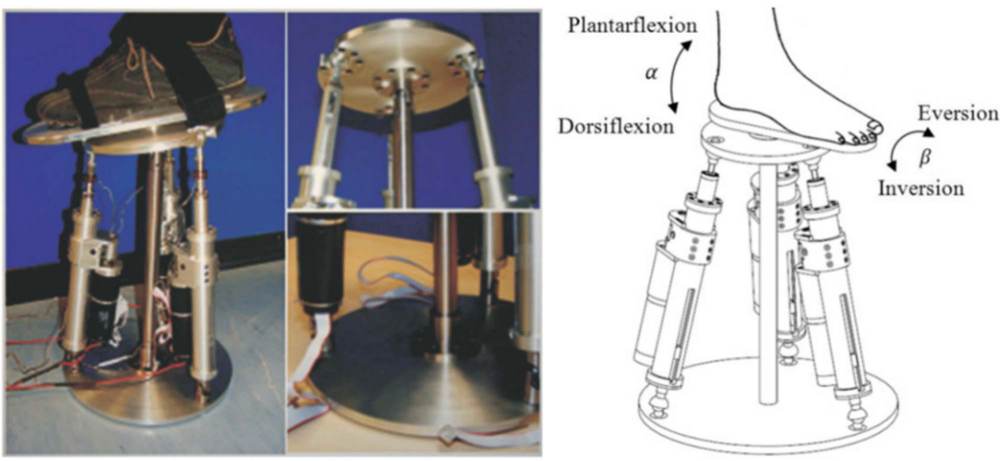


Figure 5: Wearable ankle rehabilitation device.

3.4 Rutgers ankle

The *Rutgers ankle* [8] is based on the Gough-Stewart platform with six degrees of freedom. Six degrees of freedom lead to a great flexibility in the foot control, but they increase the final cost of the device. The translational degrees of freedom allowed by the device are considered redundant and unnecessary for ankle rehabilitation movements.

Figure 6: Rutgers Ankle.

4 PKAnkle

4.1 General aspects

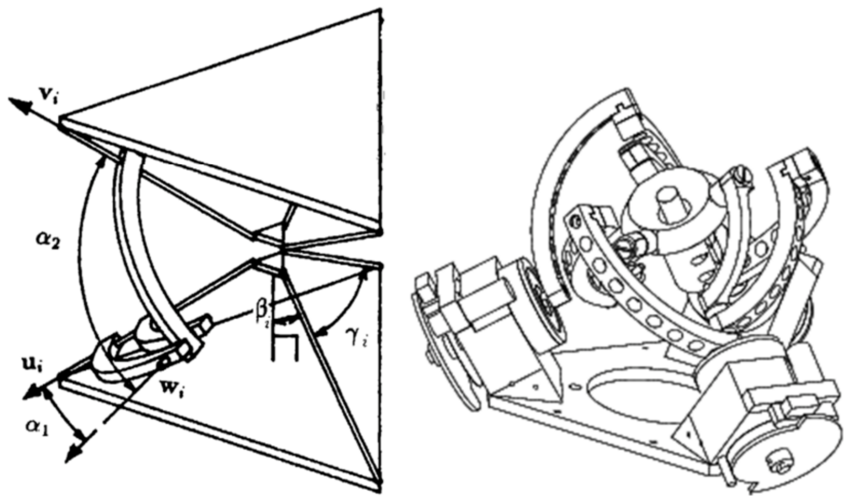
The kinematics of foot movements (Section 2) has led to the conception of a mechatronic device based on a spherical parallel kinematic scheme, characterized by three degrees of freedom, centered in the center of the ankle. The kinematics of the mechanism is characterized by a mobile platform with three rotational degrees of freedom. From the application point of view this mechanism allows to constraint the position of the ankle center and to obtain a pure rotational movement of the foot around a point centered in the ankle. Other ankle devices with more than one degree of freedom have been conceived and exist, but they are characterized, in general, by not respecting the ankle center of rotation (*e.g.*see Section 3.3). The importance of this aspect is highlighted in Section 2.2.

4.2 Kinematics

The main aspect to take into account designing a machine based on a parallel spherical kinematic scheme is the intrinsic coupling among the various degrees of freedom and the conditioning index of the machine (not everywhere unitary as Cartesian machines). The $\underline{R}$RR scheme, introduced by Gosselin, applied in the prototype named AgileEye [9] and represented in Fig. 7, is considered a great solution to:

- design an innovative rehabilitation device with the requirement of constraining the center of rotation of a mobile platform without a physical center of rotation;
- obtain a compact (*i.e.*not high) device to be used by seated patient;
- realizing a device with good kinetostatic performances in the whole foot range of motion.

As demonstrated in [10] the kinematics is characterized by a conditioning index which is maximum if the angle between the rotational axes of each link is $\pi/2$. Another property of this



(a) Kinematic scheme (b) Agile Eye representation

Figure 7: Gosselin's $\underline{\text{R}}$RR parallel kinematic architecture

manipulator is that the conditioning index decreases very slowly moving away from the isotropic configuration. Thus, the average conditioning is very good for a finite region of the workspace centered on that configuration (Fig. 8).

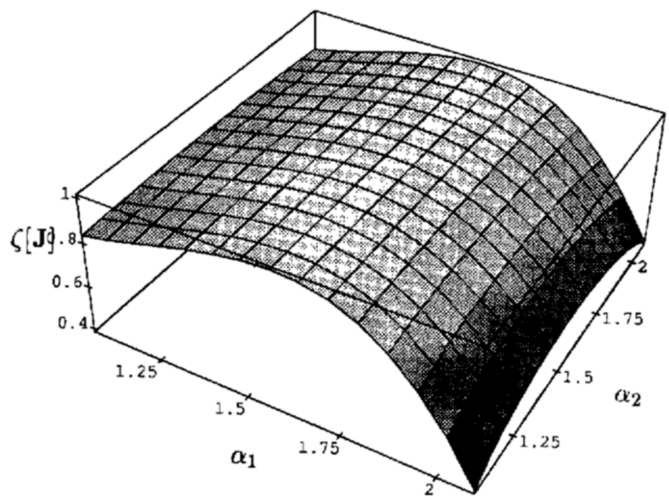


Figure 8: Kinetostatic conditioning number.

Consequently the *PKAnkle* design parameters are:

- $\alpha_1 = \pi/2$
- $\alpha_2 = \pi/2$
- $\gamma_i = \pi/2$

4.3 Design and dimensioning

In order to correctly dimension the mechanical components of *PKAnkle* a number of simulations have been carried out parametrizing the main dimensions of the device.

4.3.1 Multibody simulations

A simplified dynamic model of the device has been implemented and used to evaluate actual forces and torques of the device (Fig. 9).

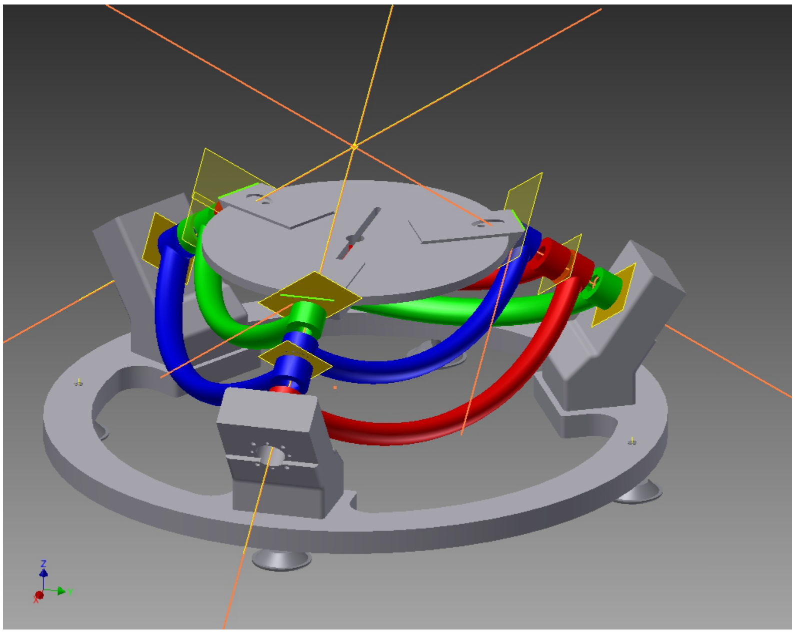
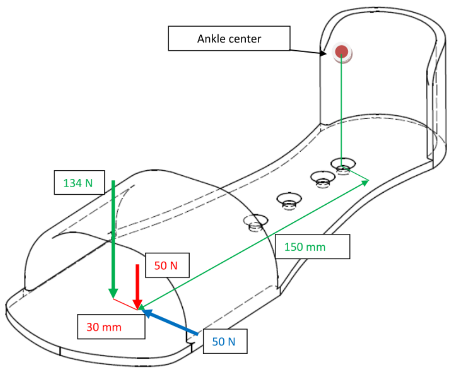


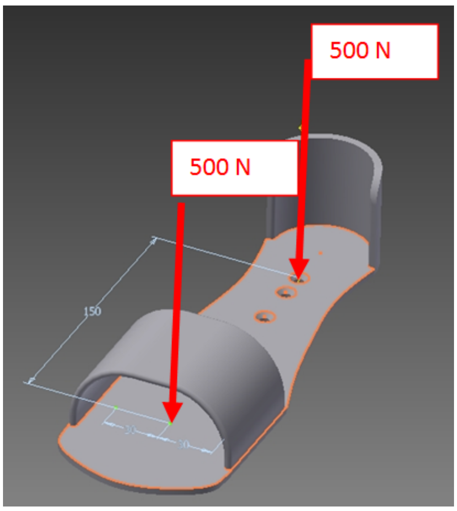
Figure 9: Simplified dynamic model of *PKAnkle*.

Dynamic simulations have been performed with two distinct conditions:

- Maximum functional loads, exerted voluntary or involuntary by human muscles, to dimension maximum motor torques (Fig. 10(a)).
- Maximum loads to dimension structural dimensions of joints (bearings) and links to avoid



(a) Maximum operational load

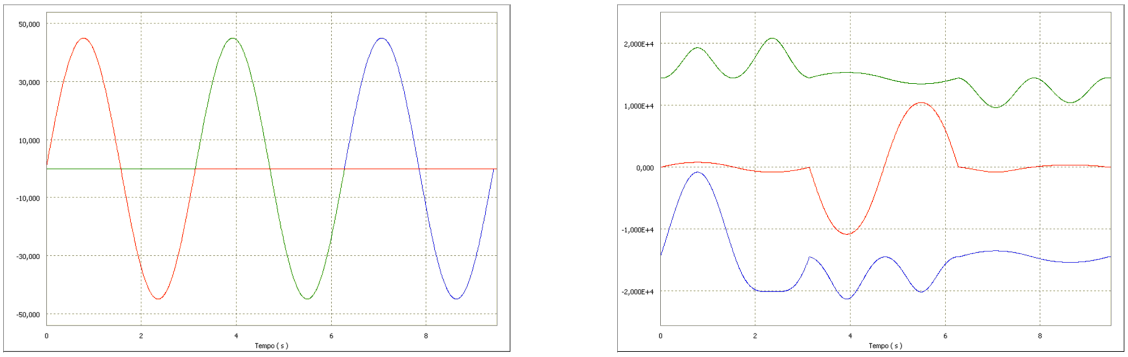


(b) Maximum allowed load

Figure 10: Load conditions

the structure of *PKAnkle* to collapse in case of bad loading conditions (*e.g.*patient standing on the device (Fig. 10(b)).

In Fig. 11(b) are represented motor torques as function of joint positions shown in Fig. 11(a).



(a) Joint positions (b) Motor torques

Figure 11: Motors torques dimensioning

4.3.2 FEM simulations

Additional FEM simulations has been performed to correctly dimension links sections and dimensions, and bearing loads. In Fig. 12 are represented FEM load conditions for *Link 1* and *Link 2* (refer to Fig. 17 for nomenclature). Forces and torques values are reported in Table 1, computed by multibody simulations.

Table 1: FEM links load conditions

	Link 1	*Link 2*
Axial force $[N]$	243.5	312.6
Radial force $[N]$	312.6	243.5
Torque $[Nm]$	52.9	0

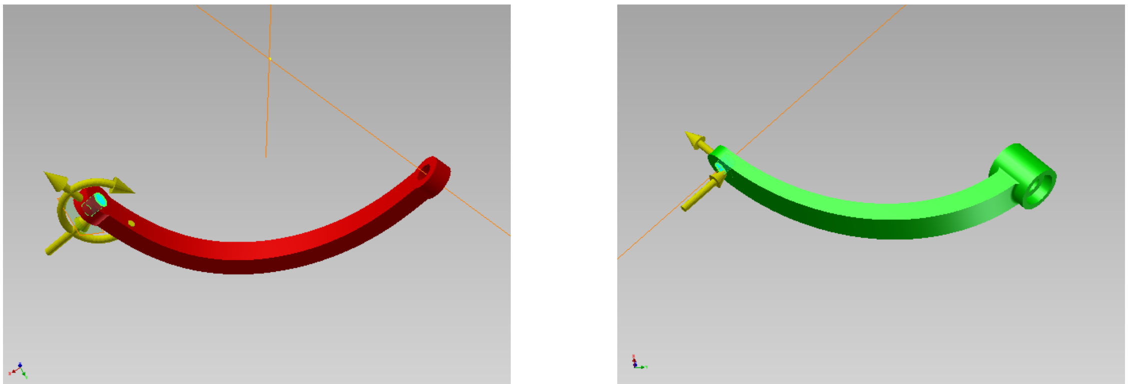
Designed links materials is Ergal alluminium alloys, whose material properties are:

- Young modulus = 71.7 GPa
- Poisson coefficient = 0.33
- Carico Snervamento = 503 MPa

In Fig. 13 and Fig. 14 are reported, respectively, resulting Von Mises maximum stresses and maximum displacements. Obtained numerical values are compatible with material properties and application requirements.

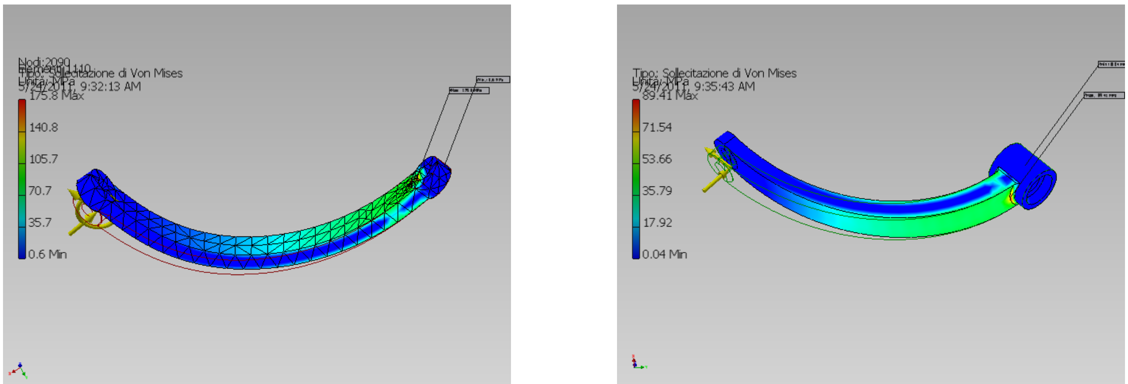
4.4 Mechanical project

The design activity of the ankle rehabilitation device led to the final design of the first prototype of *PKAnkle*. Some views of the prototype which will be manufactured are shown in Fig. 15, Fig. 16, Fig. 17.



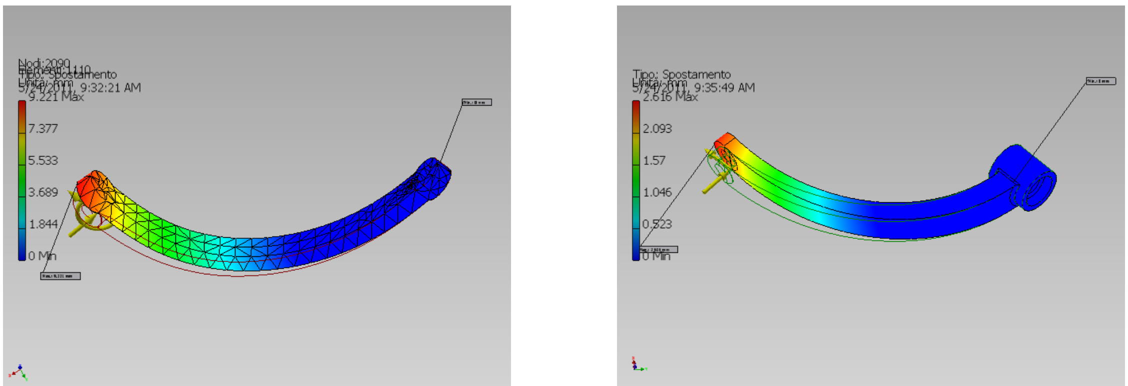
(a) Link 1 (b) Link 2

Figure 12: FEM links load conditions



(a) Link 1 (b) Link 2

Figure 13: Maximum links Von Mises stress



(a) Link 1 (b) Link 2

Figure 14: Maximum links deformations

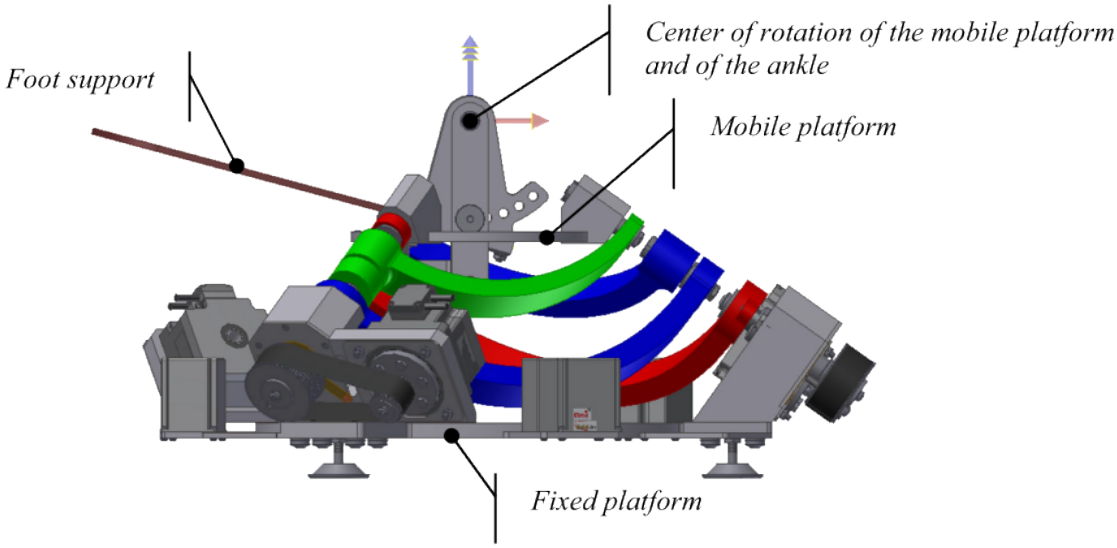


Figure 15: Lateral view of *PKAnkle*.

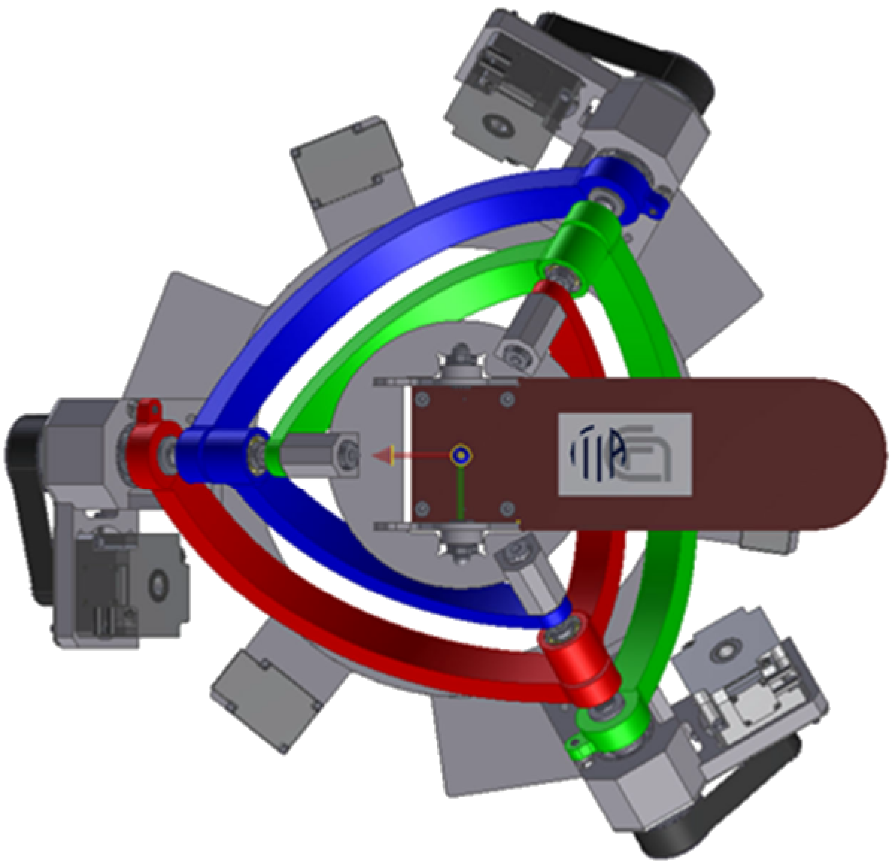


Figure 16: Top view of *PKAnkle*.

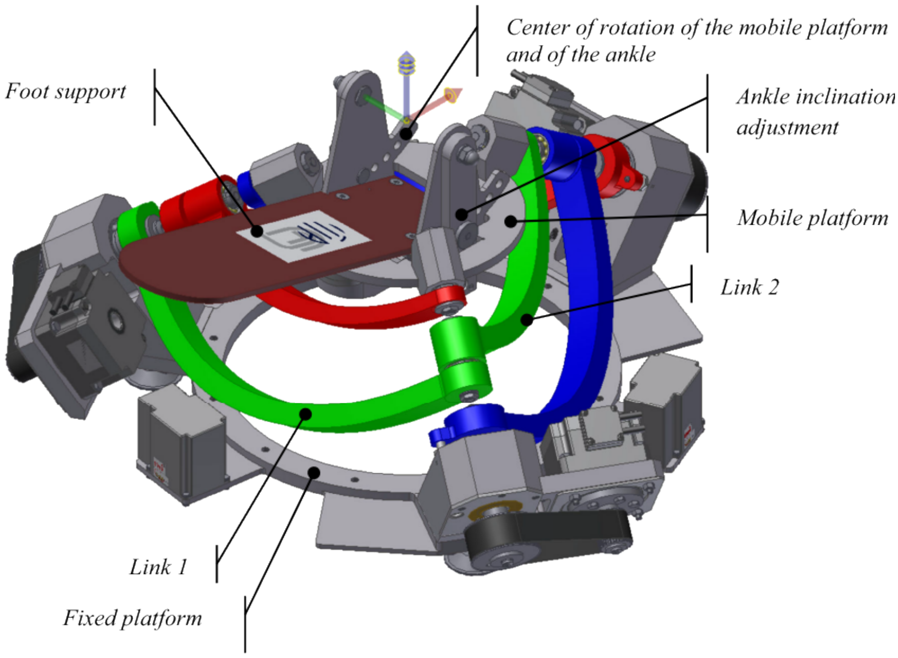


Figure 17: 3D view of *PKAnkle*.

5 Future activities and developments

PKAnkle is currently being machined and assembled. The next activities will be mechanical and control tests to verify the correct functioning of the device. Meanwhile the documentation to require the approval by ethic committees of clinical institutions will be prepared and submitted, to test the actual behavior and benefits of the device for patients.

From a design point of view simplifications and alternative design will be evaluated to improve performances and reduce costs. For this reason the next development and prototype version of the device will likely be characterized by a new kinematic architecture. It has been conceived, together with the activities presented so far, during a collaboration with the *University of Ontario*

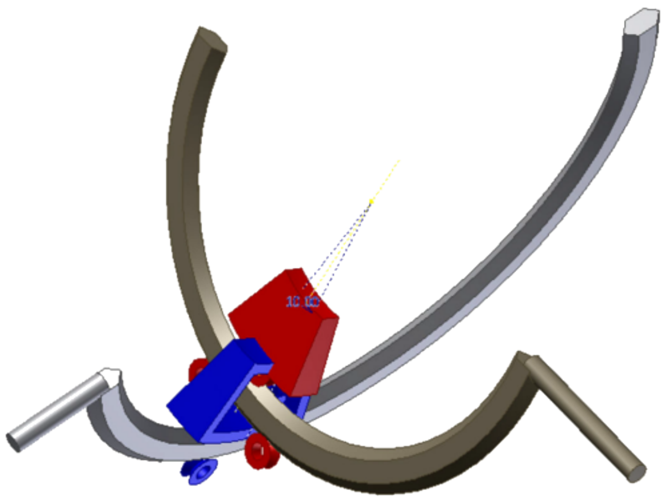


Figure 18: Decoupled spherical parallel kinematics.

- *Institute of Technology* (*UOIT-Canada*), characterized by a decoupling of rotational degrees of freedom. Possible advantages of this mechanism, with respect to other spherical parallel kinematic mechanism, are the lower number of mobile parts and the smaller footprint.

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