2014 5th IEEE RAS & EMBS International Conference on
Biomedical Robotics and Biomechatronics (BioRob)
August 12-15, 2014. São Paulo, Brazil

Ergonomics and kinematic compatibility of *PKankle*, a fully-parallel spherical robot for ankle-foot rehabilitation*

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***Abstract*— *PKankle* is a robotic device based on a fully-parallel kinematic architecture and specifically designed for the neuro-rehabilitation of the ankle-foot complex. The peculiar kinematics allows the foot support to rotate, with good approximation, about the instantaneous center of rotation of the foot. An adjusting mechanical system allows the device to be employed in different patient positionings. Moreover, it features an integrated load cell for measuring subject interaction forces/torques, both to close impedance-based control loops and to obtain valuable clinical data, and a synchronized electromyographic acquisition system to analyze patient's muscular activity. The present work describes kinematic and control aspects specifically addressed to enhance its ergonomics and physiological compatibility to the actual mobility of the ankle-foot complex. Preliminary experimental activities, performed by healthy subjects, have been carried out to assess the effectiveness of the adopted solutions.**

I. INTRODUCTION

A. Medical requisites and application

Loss of motor control and pathological fixed postures are common problems in the Upper Motor Neuron Syndrome (UMNS). The equinovarus foot is the commonest posture seen in the lower extremity of these patients. Equinovarus limits dorsiflexion motion during single limb support when the foot is stationary. The lack of available dorsiflexion results in hyperextension thrust of the knee and retrained forward translation of the body center of gravity. Commonly, equinovarus, in addition to loss of motor control, alters the cyclical kinematic pattern of the lower limb and trunk during gait, inducing compensations for the less involved limb, pain, fatigue and impaired function. The compensatory movements necessary for ambulation produce exaggerated lateral displacements of the center of gravity which results in increased energy expenditure and negatively impact the patients activities of daily living [1]. Rehabilitation therapies addressing prevention/treatment of stiffness and equinovarus focus on passive mobilization. The goal is to maintain the passive range of ankle motion. Besides stretching of the plantar flexor muscles, also inversion and eversion mobilization is important to allow proper foot contact and base support. Proper exercises are performed to strengthen dorsiflexor muscles and improve selective motor control. In this case, the goal is to reduce the *learning nonuse* due to weakness of the dorsiflexor muscles and to preserve the elastic properties of the dorsi-plantarflexor muscles.

B. Biomechanics of the ankle-foot complex

The anatomical joints constituting the ankle-foot complex taken into account for the purposes of this work[1] are: i) the tibio-tarsal joint (or talo-crural), ii) the sub-talar joint (talus-calcaneus) and iii) the mid-tarsal joint (talus - calcaneus - cuboid - navicular) [2].

A mechanical model approximating the actual ankle kinematics is made up of two main joints. The former is the tibio-tarsal joint, determining the foot flexion-extension movement. It can be considered as a single-degree-of-freedom rotational joint with a moving axis of rotation [3], [4]. The second one is an ideal joint approximating the combined effect of the subtalar and mid-tarsal joints, causing a supination-adduction-extension movement of the foot, defined as *inversion*, and oppositely an abduction-pronation-flexion movement, defined as *eversion*. In the literature this second axis is typically defined as *subtalar axis*. This ideal joint is not precisely enough described by a merely rotational joint, while an instantaneous helical axes is suitable. It largely varies person by person in the two direction of

[1]Metatarsal joints are here neglected because they are constrained by the foot support of the described device.

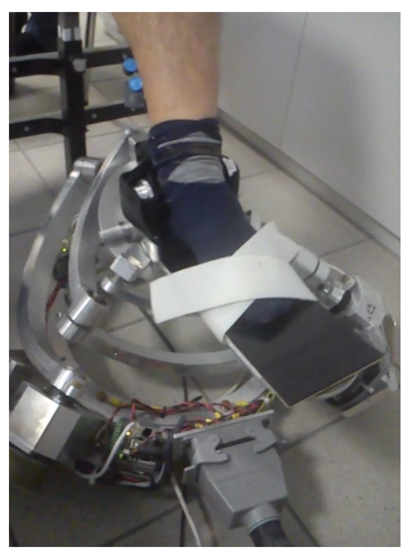

Fig. 1. The *PKankle* device.

*This work was partially supported by the Italian Lombardy region within the *RIPRENDO@home* project.

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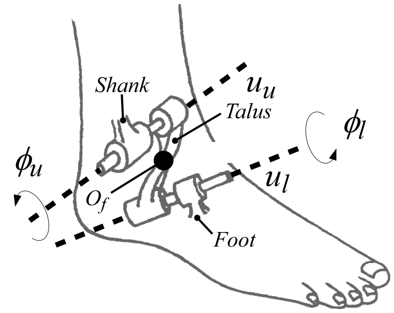


Fig. 2. Mechanical model of the ankle-foot complex, as reported in [6].

rotation but, averagely, almost all the authors agree that its medium values are inclined about $40°$ in the sagittal plane and $15-30°$ for the antero-medial deviation in the transverse plane [4], [5] . Moreover the foot-ankle complex does not have a single fixed center of rotation: based on the anatomy of the foot, it is plausible that the instantaneous axes of rotation of the aforesaid joints never intersect one each other.

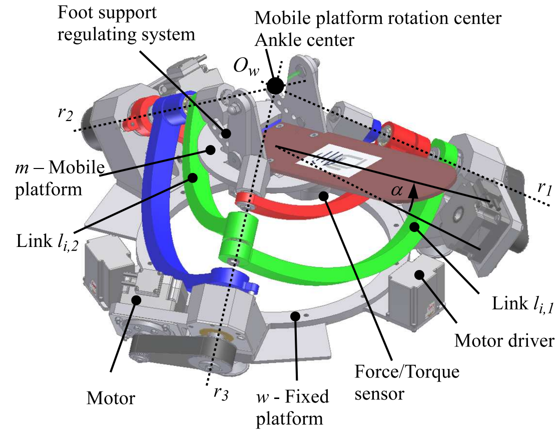
In a simplified model, the ankle-foot complex can be modeled as a three-segment system, connected by two ideal hinge joints: the talocrural and the subtalar joints [6]. Along the proximal-distal direction, the first joint represents the talo-crural articulation and determines the flexion-extension movement of the foot (rotation by ϕ_u about u_u in Fig. 2). This hinge joint has a fixed rotation axis defined as the axis that ideally connects the malleoli. The second joint represents the sub-talar articulation: in the standard anatomical position, it can be described by an oblique axis running approximately from antero-medio-superior to postero-latero-inferior regions of the foot (rotation by ϕ_l about u_l). The case-specific values can be obtained by an optimization method used to fit the model parameters to kinematic data of foot and shank markers, obtained during test movements [7], [8].

C. PKankle

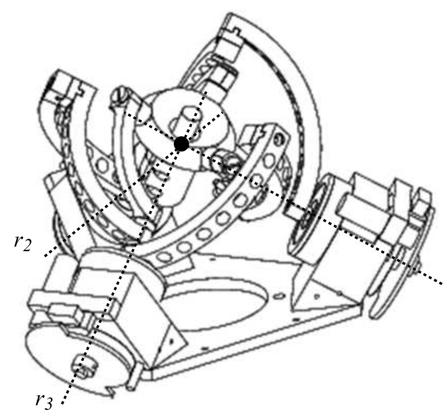
Given the actual kinematics of the ankle-foot complex, a six-degrees-of-freedom device would be the best solution to comply as faithfully as possible with its mobility. However, with the aim of developing a relatively simple device, but flexible enough to well comply with the actual range of motion and mobility of the ankle-foot complex, a rehabilitation device, named *PKankle*, characterized by a fully-parallel spherical kinematic architecture has been designed and realized [9]. In this paper, kinematic aspects specifically faced to allow its use in an ergonomic and physiologically compatible way are illustrated in Section II. Subsequently, results related to kinematics, dynamics and EMG activity during experimental tests performed by healthy subjects to assess the ergonomic performance of the device are reported in Section III.

II. MECHANICS

PKankle is a fully-parallel spherical robot for the ankle-foot rehabilitation with a $(RRR)_3$ topological structure



(a) *PKankle* mechanics: the mobile platform m, equipped with a proper load cell, rotates spherically about O_w, intersection point of the rotational axes r_1,r_2,r_3 of the actuated joints constrained to the fixed platform $\{w\}$. The α angle defines the inclination of the foot support w.r.t to m, through a proper mechanical regulating system. The kinematics is made up of three couples of rigid links connected by rotational joints.



(b) The parallel spherical kinematic structure of the *Agile eye* conceived by C. Gosselin [10].

Fig. 3. CAD models of *PKankle* and *Agile eye*.

(Fig. 3). Exploiting the spherical kinematic structure conceived by C. Gosselin [10], [11], *PKankle* has been designed through a proper structure optimization, link rearrangement and actuation dimensioning, in order to comply with the actual requirements of the ankle neuro-muscular rehabilitation [9]. In order to properly proceed with the description, it is convenient to denote by:

- $\{f\}$ and O_f a generic coordinate frame and its center, respectively;
- $\{\mathbf{e}_{f,x}, \mathbf{e}_{f,y}, \mathbf{e}_{f,z}\}$ the unit vectors of $\{f\}$ axes;
- $\pi_{f,ij}$ the plane defined by axes i and j of $\{f\}$;
- $\mathbf{u}_i = [u_{i,x}, u_{i,y}, u_{i,z}]$ and ϕ_i the unit vector of the rotational axis u_i and the value of rotation about it, respectively;
- $\mathbf{R}(\mathbf{u}_i, \phi_i)$ the rotation matrix corresponding to a rotation by ϕ_i about the $\mathbf{u}_i$ axis (Appendix I);
- ${}^1\mathbf{R}_2$ the rotation matrix describing the orientation of $\{2\}$ w.r.t. $\{1\}$.

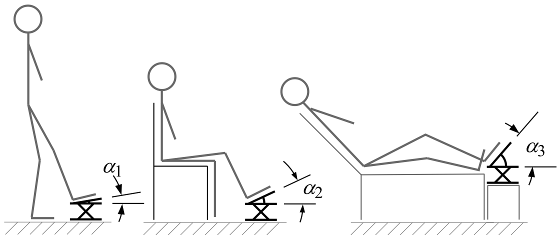
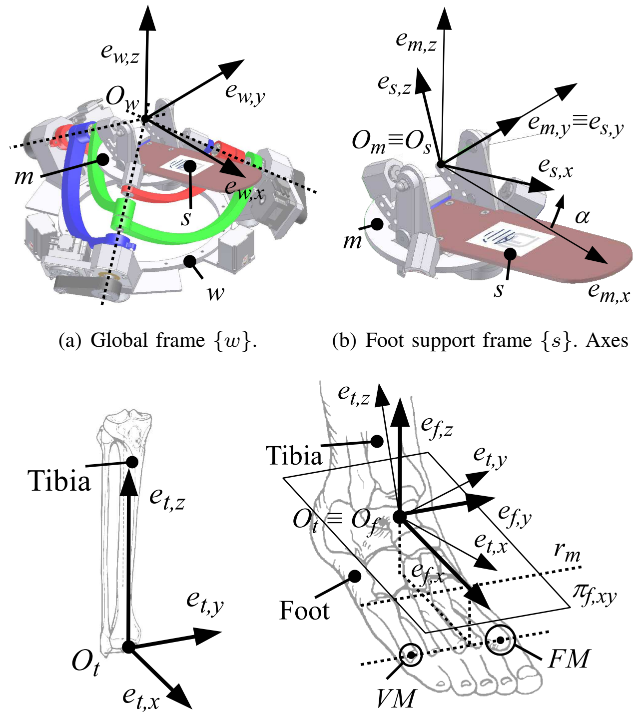


Fig. 4. Different installations of *PKankle*, according to different patient's positionings, allowed by the mechanical regulating system of the foot support.



(a) Global frame $\{w\}$. (b) Foot support frame $\{s\}$. Axes .

(c) Tibial frame $\{t\}$. (d) Foot frame $\{f\}$.

Fig. 5. Reference frames of *PKankle* and of the ankle-foot complex.

PKankle features three rotational actuated degrees of freedom constrained to the fixed platform w and whose axes r_1, r_2, r_3 intersect orthogonally in O_w. The peculiar arrangement of its parallel links constrains the mobile platform m to rotate spherically about O_w. The device has been properly dimensioned to make possible a proper positioning of the approximated ankle articular center (O_f in Fig. 2) close to O_w, in order to obtain valuable benefits in terms of therapy functions avoiding possible compensatory movements by the patient during therapy. Moreover, in order to allow a flexible employment of the device in different patient positionings, a mechanical adjusting system allows to regulate the inclination of the foot support w.r.t. the mobile platform m of the device, as schematized in Fig. 4.

The spherical kinematic structure of *PKankle* allows, theoretically, to control the foot movement as if it were constrained to the tibia by a spherical joint. However, as summarized in Section I-B, the ankle articulation cannot be easily approximated as a spherical joint. In order to induce movements to the foot, they have to be properly ergonomic, respecting the actual ankle kinematics. Moreover, considering passive or assistive rehabilitation therapies, control trajectories have to be properly compatible with the physiological movements of the ankle and, in general, properly smooth not to induce stretch reflexes or other pathological reactions. Hereafter, the kinematic coupling between *PKankle* and the ankle is described, illustrating how kinematically compatible movements can be obtained, taking into account the actual kinematics of the ankle. Afterwards, the main aspects of the cycloid-based motion law generator, implemented to obtain a flexible and ergonomic use of the device during therapies, are depicted.

A. Kinematics

Referring to Fig. 2 and according to the nomenclature reported in [6], let us denote by u_u and u_l the *upper ankle rotation axis* and the *subtalar rotation axis*, respectively. Similarly, let us denote by ϕ_u and ϕ_l their respective rotation angles. Referring to Fig 5, let us consider the following reference frames:

- $\{w\}$ - fixed platform w;
- $\{m\}$ - mobile platform m;
- $\{s\}$ - mobile foot support s;
- $\{t\}$ - tibial bone t;
- $\{f\}$ - foot f.

In order to define anatomical reference frames, reference axes have been defined as function of foot anatomical landmarks, as presented in [12]. In particular *FM* and *VM* denote the dorsal aspects of the first and fifth metatarsal, respectively, defining the direction of $e_{f,y}$. Refer to Fig. 5(d) for a detailed graphical representation.

The orientation of the foot support s, determined by the *PKankle* kinematic chain, is defined by the transformation ${}^w\mathbf{R}_s = {}^w\mathbf{R}_m{}^m\mathbf{R}_s$. On the other side, the orientation of the foot, determined by the kinematic chain of the ankle articulation, is defined by ${}^w\mathbf{R}_f = {}^w\mathbf{R}_t{}^t\mathbf{R}_f$. Moreover, we can consider $\{f\} \equiv \{s\}$ if the foot is correctly placed on the foot support, since i) O_f and O_s are nearly coincident, ii) $e_{f,x}$ and $e_{f,z}$ are nearly parallel to $e_{s,x}$ and $e_{s,z}$, respectively. Therefore, the loop equation of the closed kinematic chain defined by the *PKankle* mechanism and the human ankle articulation, when the foot is placed on the foot support, is:

$$ {}^w\mathbf{R}_m\,{}^m\mathbf{R}_s = {}^w\mathbf{R}_t\,{}^t\mathbf{R}_f \tag{1} $$

where ${}^t\mathbf{R}_f = \mathbf{R}(\mathbf{u}_u, \phi_u)\mathbf{R}(\mathbf{u}_l, \phi_l)$ due to the ankle kinematics (Fig. 2), and ${}^m\mathbf{R}_s = \mathbf{R}(\mathbf{e}_{m,y}, \alpha)$, due to the rotational constraint between $\{m\}$ and $\{s\}$ (Fig. 5(b)). Moreover, the foot support is supposed to be adjusted so that $\{t\} \equiv \{s\}$ if $\{m\} \equiv \{w\}$ (device *home position*), leading to have

$$ {}^w\mathbf{R}_t = {}^m\mathbf{R}_s \tag{2} $$

It is convenient to define ergonomic and physiological compatible movements of the device referring to frame $\{t\}$, making them independent from the actual orientation of the foot support. Therefore, given a desired orientation of the

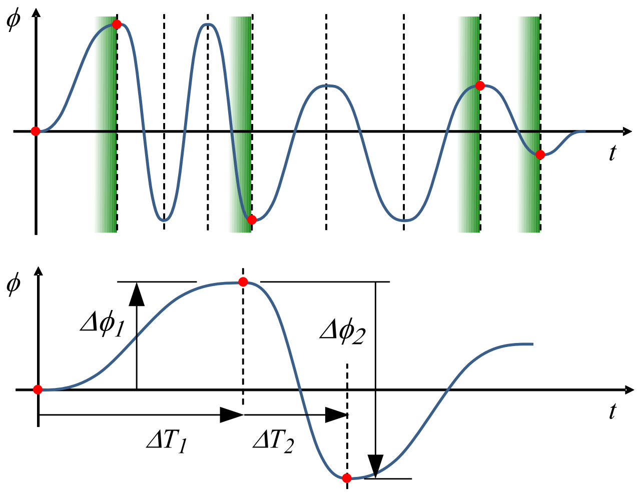


Fig. 6. Representation of a motion law made up of a series of different cycloid segments.

foot ${}^t\mathbf{R}_f$, referring to (1) and (2), the orientation of the mobile platform m is given by

$$^w\mathbf{R}_m = {}^m\mathbf{R}_s\,{}^t\mathbf{R}_f\,{}^m\mathbf{R}_s^{-1},$$

defined by the anatomical directions of axes $\mathbf{u}_u$ and $\mathbf{u}_l$, their angles ϕ_u and ϕ_l, and the actual orientation α of the foot support. Given the matrix ${}^w\mathbf{R}_m$ it is straightforward to compute the inverse kinematics of the device as reported in [11] in order to obtain the required actuators positions to properly control the rehabilitation device. This formulation is suitable to model ankle-foot rotation axes, both considering simpler and more complex models (Section I-B), approximating anatomical rotational axes as passing through O_f.

B. *Motion control*

According to medical and rehabilitation therapy needs, the device is required to perform smooth and continuous rehabilitation movements, with the possibility of varying both motion frequency and amplitude, according to medical indications or other external signals. As presented in Section II-A, motion movements can be defined according to the actual ankle-foot kinematics, properly controlling ankle coordinates ϕ_u and ϕ_l values. In order to define physiologically compatible motions, avoiding excessive articular stress, stretch reflexes or other unphysiological reactions in result of sudden changes in speed and acceleration, the implemented motion profile generator properly combines a series of cycloidal motion segments, as illustrated in Fig. 6. The cycloid is a motion law commonly accepted and used to achieve smooth motion profiles, approximating in an acceptable way the polynomial formulation required to achieve minimum jerk trajectories, and allowing an efficient and straightforward implementation (Appendix II). The motion law generator concatenates distinct cycloidal segments at their zero-velocity points, guaranteeing a C^1 continuity (*i.e.* no discontinuity in the velocity profile) of the entire motion profile. It allows to modify smoothly and interactively (*e.g.* through the graphic user interface) amplitude and motion frequency through the rehabilitation therapy, without the necessity of discontinuing it. If required by therapeutic needs, the openness of the control architecture [9] will allow the implementation of other motion profiles (*e.g.* to emulate the gait).

III. EXPERIMENTAL ASSESSMENT

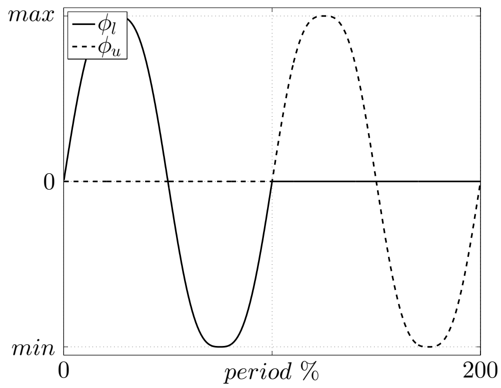
PKankle was tested on 5 healthy (neurologically and orthopedically intact) subjects (5 males, 32±8 years old). For each patient acquisition of tibialis anterior m. (TA), soleus m. (SOL), gastrocnemius lateralis (GAL) and medialis m. (GAM) activity was performed during gait at self-selected speed and during mobilization with *PKankle*. *PKankle* movements consisted in: 1) Plantar-Dorsiflexion Movement (PDM), (2) Full Circling Movement of the foot (FCM), and 3) a complex movement of plantarflexion and dorsiflexion with alternately superimposed inversion and eversion, hereafter called Half Circling Movement (HCM) (Fig. 7). The three kind of movements were performed in two different conditions: firstly, the subject was asked to try to relax as much as possible during passive mobilization, secondly, he was asked to participate to the movement trying to slightly anticipating it. All trials consisted in at least 12 repetitions. Duration of the single movements cycle was 2 seconds (1 second each phase).

Stance and swing phases were identified during gait using two pressure soles (FreeEMG 300, BTS, Italy) attached under the bare foots. Phases during *PKankle* mobilization were identified using the pitch angular displacement given by the controller. As the Freeemg 300 is integrated in the *PKankle* controller, probes and electrodes used were the same and identically placed during the gait and all *PKankle* trials.

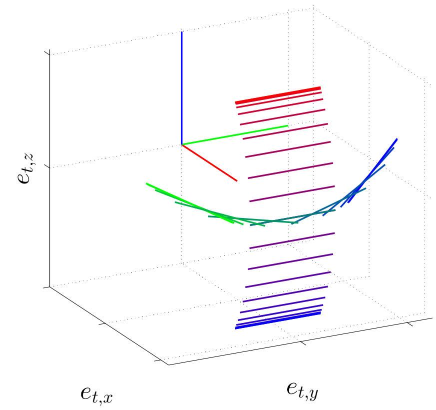
A. *Results*

All five subjects completed all trials with no problems referring high comfort, both during passive and active (when participating) mobilization. During all movements no subject presented any abnormal activation of any of the four examined muscles.

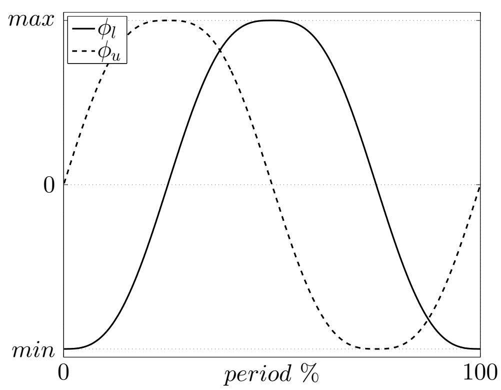
All patients were able to completely relax during passive mobilization. Two of them instinctively tended to participate by activating the tibialis anterior muscle at the end of the dorsiflexion phase. Active participation is demonstrated by both the presence of EMG activity of the tibialis anterior muscle and the consequent reduction of the dorsiflexion torque M_y that *PKankle* must generate to complete the movement (Fig. 8). During participated movements a good alternation between tibialis anterior and the plantiflexor muscles group is highlighted in all five subjects. Fig. 9(b) shows one of the subject's neuromuscular activation pattern during participated dorsi-plantarflexion movement. The pattern highly resembles the one of the same subject during gait (Fig. 9(a)).



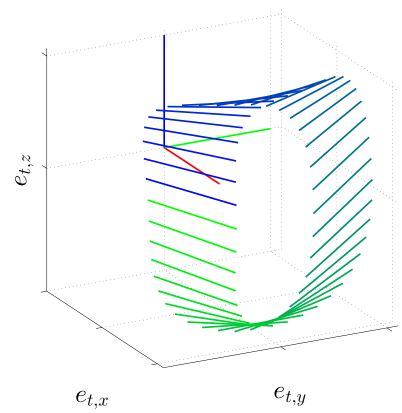
(a) Motion law decoupling Plantar-Dorsiexion Movement (PDM) and Inversion-Eversion Movement (IEM).



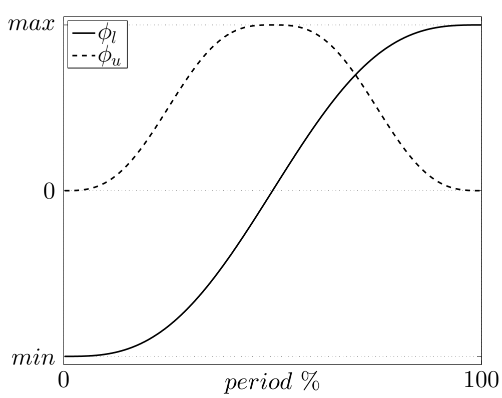
(b) Tridimensional reprensentation of PDM and IEM.



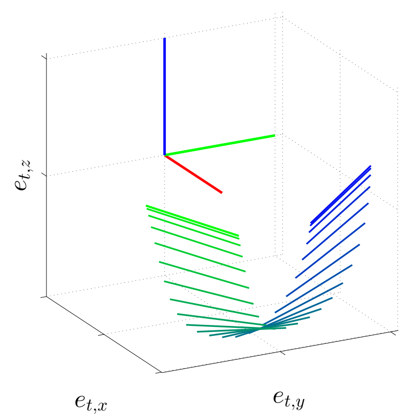
(c) Motion law of the foot Full Circling Movement (FCM).



(d) Tridimensional reprensentation of FCM.



(e) Motion law of the foot Half Circling Movement (HCM).



(f) Tridimensional reprensentation of HCM.

Fig. 7. Ergonomic trajectories obtained properly combining motion of ankle-foot coordinates ϕ_l and ϕ_u. The triads reported in tridimensional plots refer to $\{t\}$ and the segments trails represent the motion of line r_m depicted in Fig. 5(d), projection of the line passing through dorsal aspects of the first and the fifth metatarsal, FM and VM respectively, on plane $\pi_{f,xy}$.

B. Discussion

PKankle movements were perceived by subjects as highly comfortable. This is probably due to two main reasons. On the one hand because the kinematics of *PKankle* respects the ankle joint kinematics, on the other hand because velocities profiles are always smooth avoiding sudden and jerky displacements even at high velocity. This is promising considering that smoothness is recommended to avoid pathological stretch reflex and spasticity in neurological patients. Subjects were also able to participate to *PKankle*

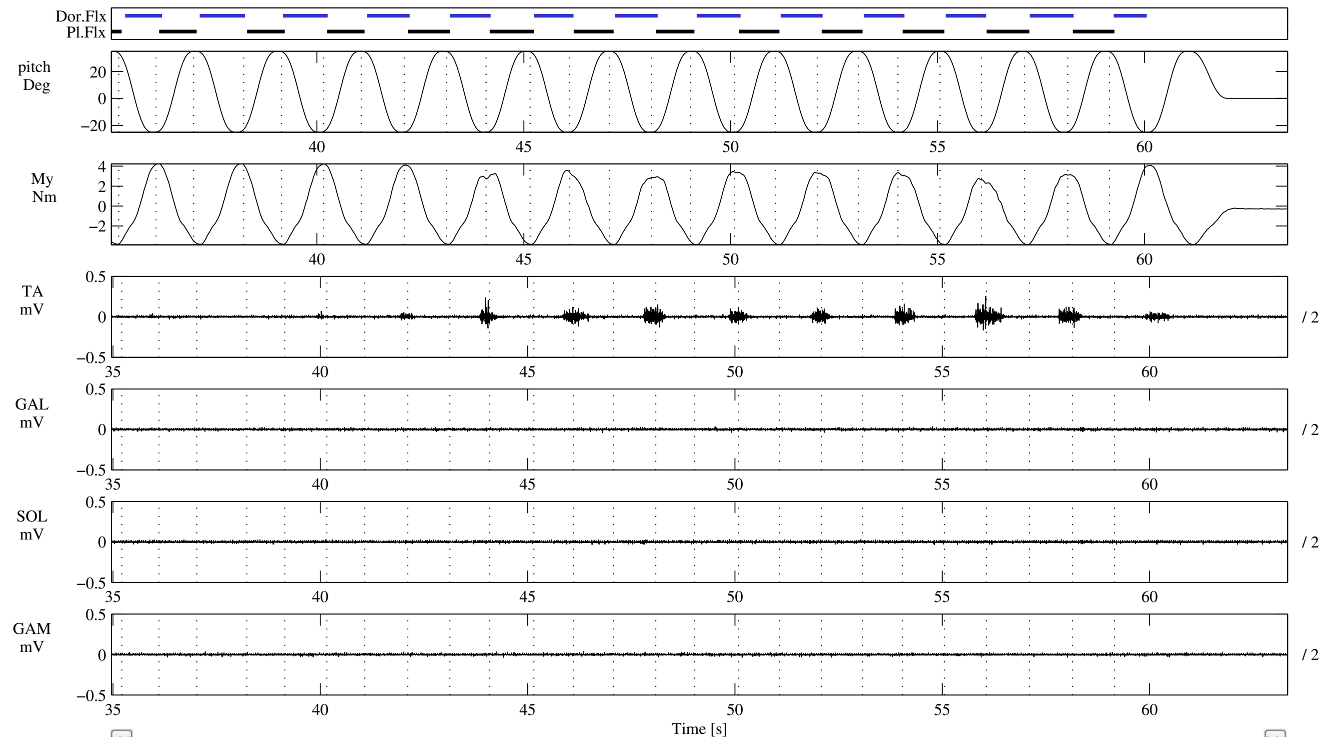
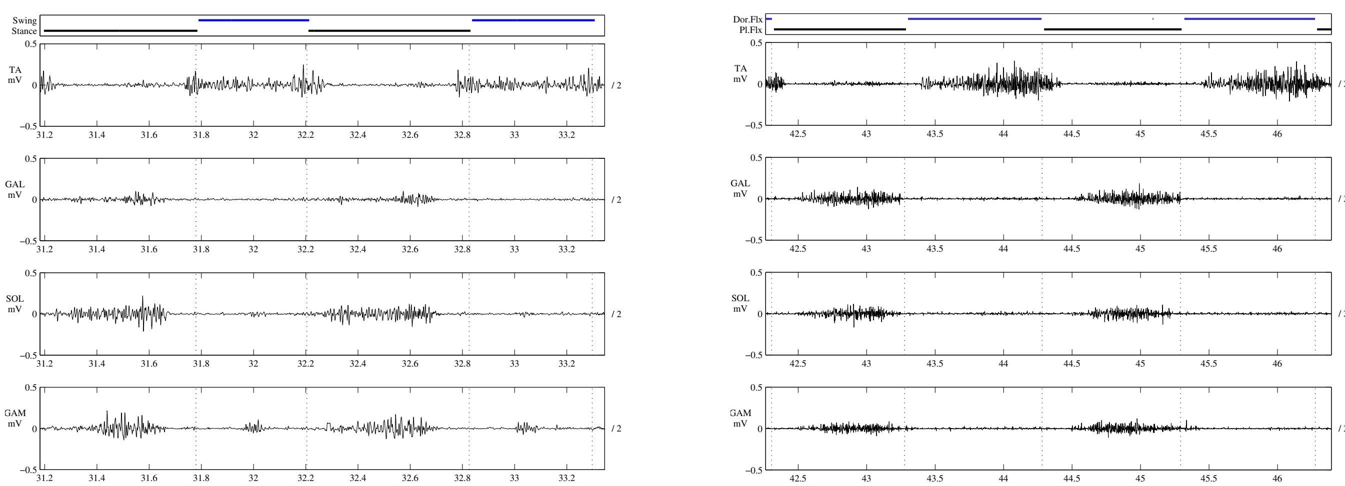


Fig. 8. Thirteen dorsi and plantiflexion cyclic movements. The subject who is asked to relax the ankle muscles, instinctively begins to slightly participate starting from second 43. Tibialis Anterior (TA) activity at the end of the dorsiflexion phase and a consequent reduction in external dorsiflexsion torque (M_y) supplied by *PKankle* are evident. The dosiflexion and plantiflexion phases are reported in blue and black respectively in the upper part of the figure.



(a) Neuromuscolar activation pattern during gait.

(b) Neuromuscolar activation pattern during *PKankle* planti-dorsiflexion exercise.

Fig. 9. Left panel (a) shows the EMG activity of TA,GAL,SOL and GAM during 2 gait cycles. Right panel (b) shows the EMG activity relative to the same subject who actively participates to the planti-dorsiflexion movement imposed by *PKankle*. The neuromuscolar activation pattern during *PKankle* exercise highly resembles the one during gait. Movement phases are reported in the upper part of the figures: stance and plantiflexion are indicated with black lines, swing and dorsiflexion with blue lines.

imposed movement, showing a good alternation between planti and dorsiflexor muscles activity like in gait. This is encouraging suggesting that *PKankle* could probably be used also for active reinforcing dorsiflexion exercises. Patients may be asked to participate to the imposed movement like in the trials presented in this paper. These preliminary results on healthy subjects will be integrated in the next future with results on stroke patients. Quantitative analyses will be done to compare agonist and antagonist cocontactions values. Comparisons will be done both between healthy and pathological subjects and between *PKankle* mobilization and gait.

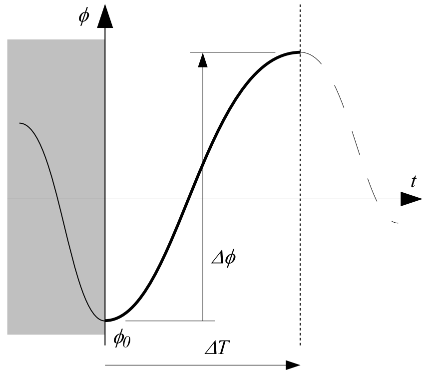


Fig. 10. Parameters used to evaluate cycloid segments.

IV. CONCLUSIONS

The peculiar three-degrees-of-freedom parallel kinematic structure of *PKankle*, a device specifically designed for the neuro-muscular rehabilitation of the ankle-foot complex, allows to perform highly ergonomic motions with respect to its actual mobility, easily obtainable both in terms of trajectories and motion laws. The fully spherical motion of the foot support, centered nearby the point of least distance between the upper-ankle and the subtalar rotation axes, optimize the physiological compatibility to the ankle articulation, as can be seen by the multi-signal analysis of kinematics, dynamics and electromyographic activity data. The estimation of anatomical axes is currently obtained on the basis of the medical staff experience and literature data. Future developments will be focused on the implementation of admittance control algorithms exploiting the installed torque sensor, to increase the anatomical compatibility of the device movements to the actual ankle kinematics, leading moreover to an accurate estimation of ankle anatomical axes. However, it is worth to mention that the presence of foot soft tissues partially relaxes apparent strict requirements related to axes alignment. In fact, the motion of *PKankle* has been perceived comfortable by a set of healthy subjects even considering a (reasonable) axes misalignment, thanks to foot sole tissues compliance. Subsequently, in order to allow the use of the device by patients with very poor residual motion abilities, EMG activity will be used as feedback signal for an additional control loop. Torque and EMG signals will also be used for spotting abnormal cocontractions of the plantiflexor muscles in order to automatically invert the direction of the movement.

APPENDIX I
AXIS-ANGLE REPRESENTATION OF A ROTATION

Let us consider a rotation by ϕ about the $\mathbf{u} = [u_1, u_2, u_3]$ axis. The corresponding rotation matrix is [13]:

$$\mathbf{R}(\mathbf{u}, \phi) = \begin{bmatrix} 1 + (u_1^2 - 1)v & -u_3 s + u_1 u_2 v & u_2 s + u_1 u_3 v \\ u_3 s + u_1 u_2 v & 1 + (u_2^2 - 1)v & -u_1 s + u_2 u_3 v \\ -u_2 s + u_1 u_3 v & u_1 s + u_2 u_3 v & 1 + (u_3^2 - 1)v \end{bmatrix}$$

assuming $s = \sin\phi$ and $v = 1 - \cos\phi$.

APPENDIX II
CYCLOIDAL MOTION LAW

Referring to Fig. 10, the cycloidal motion equation is [13]:

$$\phi(t) = \phi_0 + \Delta\phi \left(\frac{t}{\Delta T} - \frac{1}{2\pi} \sin\left(2\pi \frac{t}{\Delta T}\right)\right)$$

where ϕ_0 is the starting position of coordinate ϕ at a certain instant of time, $\Delta\phi$ is the cycloid segment amplitude and ΔT is its duration.

ACKNOWLEDGMENTS

The authors would like to thank Simone Pio Negri for the mechanical design of *PKankle*, Nicola Pedrocchi for the development of its control system, João Carlos Dalberto for its realization, Roberto Bozzi for its electrical wiring, Andrea Chiavenna for supporting data acquisition and Alessandro Scano for media preparation. The authors would like moreover to thank the medical personnel of the Villa Beretta Rehabilitation Center (Costa Masnaga, LC, Italy) for their valuable support in carrying out experimental tests.

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