An Ergonomic Dynamometric Foot Platform for Functional Assessment in Rehabilitation

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***Abstract* – This paper presents a novel platform for mono-lateral isometric force/torque measurements on the foot of human subjects. A human-centred mechatronic approach was used in the design and development of this platform, which consists of an ergonomic moving structure embedding two six-axis force/torque sensors. The height of the platform from the ground can be easily fitted to the anthropometric properties of the human body, without any reduction of the stiffness of the overall system, as strictly required for accurate isometric force/torque measurements. Thanks to a specific ergonomic study, a discrete number of height levels can be selected to meet the anthropometric requirements of a vast majority of population. The proposed platform has been designed and built for application in functional assessment of post-stroke patients, and it is currently being validated in three different clinical centres in Europe. Future application for isometric motor exercise in neurorehabilitation, and also as a generic, foot-based human-machine interface are currently under feasibility evaluation.**

***Index Terms* – Isometric force/torque measurements, functional assessment, human-machine interfaces.**

I. Introduction

After neurological injuries (e.g. stroke, traumatic brain injury, spinal cord injury) or orthopaedic injuries (e.g., fractures), the functional assessment of the foot's motor performances and their rehabilitation is crucial for the restoration of locomotion and in many tasks for independent living. Also, abnormalities in the sensorimotor control of the foot and of the big toe can be used to assess functional recovery in patients affected by many neurological diseases. For instance, recent studies about the recovery in post-stroke patients have revealed the key role of the big toe [1]

To comprehend biomechanics of the foot it is important to treat it from the perspective of rehabilitation [2]. Only few studies are reported about experiments carried out in order to study force/torques (F/T) produced by the foot during isometric contractions, in spite of the interesting potential of such measurements for functional evaluation and motor therapy [3], [4], [5].

Some motorized systems as haptic tools for foot rehabilitation, partly derived from virtual reality applications, have been also recently proposed [6], [7].

The main motivation of this work is the need, derived from intense debate with some medical research groups in neuro-rehabilitation, for new simple, low-cost but effective and usable platform for isometric F/T measurements on the foot, as well as over the whole human body [8], [9]. For example, a torque-based approach to the quantification of abnormal motor patterns in hemiparetic patients as clinical tool for the diagnosis and the assessment of the recovery was recently proposed [10].

According to the specifications derived from the rehabilitation specialists, such a new device should meet the following basic requirements:

- to record F/T data from the whole foot and, separately, from the big-toe from a patient seated on a standard wheelchair. The measurement input range should be derived from typical data on human subjects;
- the system should be designed so that it could be easily fit to the whole anthropometric characteristics of the population and used on both the right or the left feet, without requiring too much physical effort and time consumption to the therapist;
- the overall height of the system should be kept to a minimum so that the device will not require the therapist to manually lift the patient's legs to perform the measurement;
- the system should allow to perform measurement when the heel is fixed to the platform and when it is left free to be lifted by the patient. This is to allow the simulation of postures assumed by the patient when she/he is requested to perform so-called "far reaching" operations (see also Section II for more details);
- the system should be designed in a modular way, so that it could be easily integrated into platforms used to record F/T data from other body parts;
- as long as feasible, the use of motors should be avoided in order to keep the device as simple and cheap as possible.

Based on these motivations and on the above listed specific requirements received from the medical side, this paper describes a novel platform for mono-lateral isometric force/torque measurements on the foot of human subjects, mainly designed for functional assessment in rehabilitation.

The human-centred mechatronic design approach and the results of the ergonomic study on the anthropometric properties of the legs/feet of the target population are presented in Section II. Section III describes in depth the design and development process of the proposed foot device providing an extensive overview of all the possible solutions that have been considered along the debate with medical researchers before coming to a final definition of the platform mechanical structure. The detailed technical specifications of the final foot platform are provided in Section IV. In Section V the application of the device to functional assessment in rehabilitation is presented. Future work and potential other applications of the same system in the near future are discussed in Section VI, before coming to the Conclusions that are summarized in Section VII.

II. Design Approach and Ergonomic Study

A human-centered mechatronic design approach has been followed by starting from anthropometric considerations and iteratively refining the design choices in a tight debate with end-users (i.e., therapists, patients). Simulations, mock-ups and early prototypes have been extensively used to obtain direct feedback from end-users and to enable exerimental preliminary tests in the real application domain.

The suggested method for isometric force/torque measurements requires fixed, very stiff, anatomically standard and, at the same time, repeatable individual setting of the device for each patient in order to ensure reproducibility, reliability and good precision in the isometric measurements.

As a reference position, the user is seated on a chair (or a wheelchair) at height of 580 [mm] from the floor of the platform. The back of the user is 330 [mm] back from the rear side of the device.

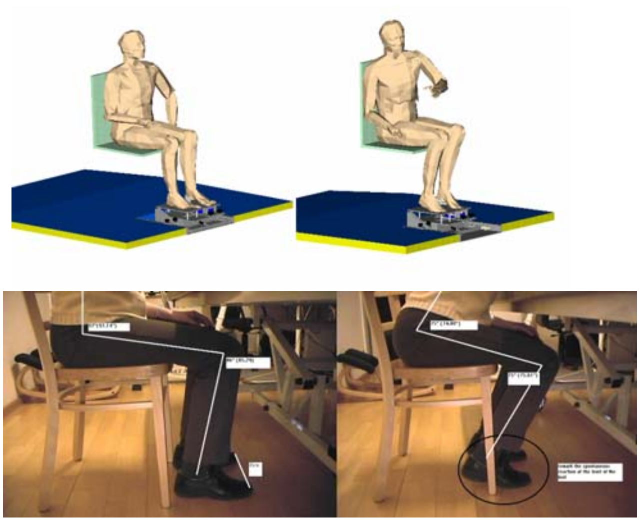

Figure. 1 CAD model used in the ergonomic study (top) and the two selected postures for the lower extremities and the feet (bottom). Position 1 (left), Position 2 (right)

In this configuration, isometric contractions in two reference postures of the lower extremities can be performed by using the proposed device (see Figure 1). In position 1, the user is seating in a neutral posture.

This position is typical for the initiation of most common tasks, such as, for instance, lifting an object or grasping task; position 2 takes into account a different posture, as the user moves the trunk forward and the feet backward: starting from this position, other tasks, such as a forward (far) reaching, can be performed.

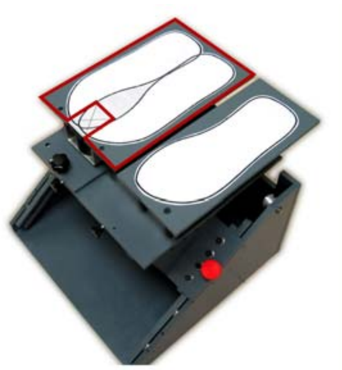

Figure 2. The mock-up of the proposed system

The anthropometric data of the European population was studied [11]. The ergonomic study was performed through CAD simulations (Pro/Engineer): a 3D mannequin model, created by using the Mannequin Pro tool, has been inserted into the CAD environment with the aim of (i) simulating the different postures according to the gender and percentile and (ii) fitting the design of the platform to the anatomical positions accordingly.

The results of this study enlightened the possibility of implementing a limited number of discrete settings, henceforth named S (Small), M (Medium) and L (Large), for the percentile values of the 25%-ile female (S size), the mean of the 50%-ile male and 50%-ile female (M size), and the 75%-ile male (L size).

Therefore, the device can be set without error to the above mentioned percentiles of the population, which represents a vast majority of the population. As a consequence of the mentioned approach, the set of the anatomical angles is fixed for any patient size. The calculated deviation from the ideal anatomical angles remains in the range ±0.5°.

This ergonomic study, by identifying only a very limited number of adjustments required to the therapist, clearly simplified the design of the overall system and represents a benefit for the therapists.

III. Design and Development of the Device

During the design phase, several concepts have been developed, according to different mechanical and anthropometric requirements,.

We consider useful to report in this section a detailed description of the design process in order to document how the direct interaction with the therapists and the patients oriented the main design choices and led to a highly acceptable final solution.

In an early phase, the design concepts have addressed the problem of the fixation of the lower extremities of the patient, using only one platform, equipped with the two sensors for the measurement on both the left and the right foot.

Two solutions have been critically analysed: one consisting of a single platform provided with a shifting mechanism for the toe sensor in order to adjust it according to left or right impaired foot; further study on the footrest, which took into account the different sizes of the foot, has led to the development of a double size platform with a common area for the big toes (and its associated sensor) for both feet.

A first mock-up was used for validating this solution. The red rectangle in Figure 2 shows the mock-up with the symmetric platform and the identified position for the sensor which measures the forces and the torques from the big toe.

This solution has the advantages to be stiff and simple; furthermore it doesn’t need any adjustment for the big toe positioning.

In order to reach the position where the patient is supposed to lift her/his heel, three different solutions have been investigated (one not supporting the heel).

Through a collaboration with the clinicians, it has emerged that the heel does not need to be supported by any structure and so solution 1 was adopted accordingly (see Figure 3).

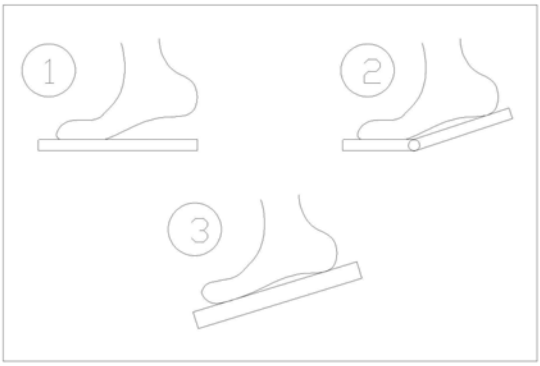

Figure 3. The three selected solutions for the heel lifting in position 2

Different solutions addressed the requirement of horizontal and vertical adjustments in the platform for fitting the anthropometrical sizes: bases with continuous (Figure 4a and 4b) or discrete adjustments (Figure 4c and 4d).

The results of the ergonomic study led toward the choice of three discrete settings (S, M and L), as already mentioned in Section II.

Three different solutions were developed: base with horizontal and vertical rails (Figure 5a), with a pipe-based skidding mechanism (Figure 5b), with a rail-based skidding mechanism (Figure 5c): the rail-based skidding mechanism was adopted.

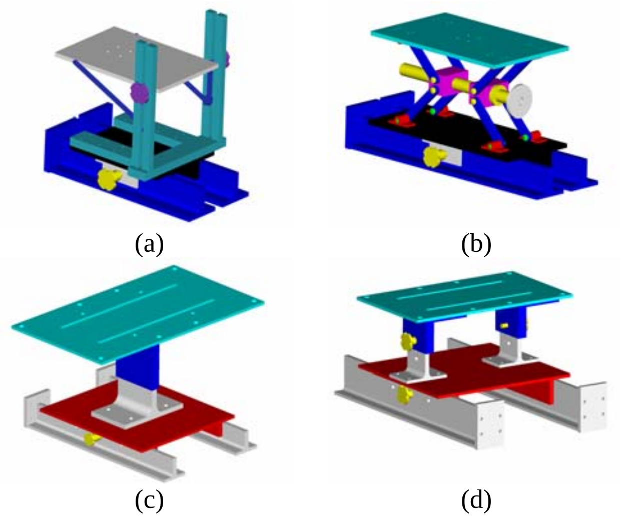

Figure 4. Different solutions for the adjustments on vertical and horizontal axes. Continuous (a), (b) and discrete settings (c) and (d)

The choice of this final solution was based on the requirements of high robustness and low encumbrance of the structure, anthropometric constraints, easiness and usability among the different settings and safety for the users.

In an iterative development approach, three different versions of the final design concept were developed.

An early prototyping technique was used: two mock-ups, in Polyvinyl Chloride (PVC) were produced, assessed by the clinical experts and by real patients, and significantly improved.

A third and final version, arisen from the first two mock-up versions, was manufactured in aluminium.

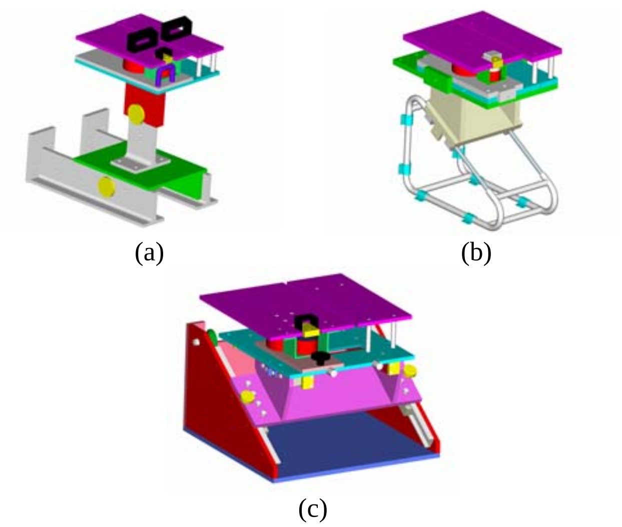

Figure 5. Different solutions for the three settings: horizontal and vertical trucks (a), tube-based skidding mechanism (b) and rail-based skidding mechanism (c)

The first version of the foot platform was a robust and simple device, but it has an high encumbrance (the user is seated 690 [mm] above the foot platform).

It didn't provide any counterbalance mechanism: the therapist had to apply a significant effort in order to support the weight of the platform during the change of the settings, according to the patient size (see Figure 6).

Figure 6. Mock-up in PVC of the first version of the foot platform

The second version (see Figure 7) was developed through a redesign of the skidding mechanism: it was pursued in order to reduce the overall encumbrance (the user is seated 600 [mm] above the foot platform) and to provide a counterbalance mechanism.

This version was less robust and more complex than the previous version.

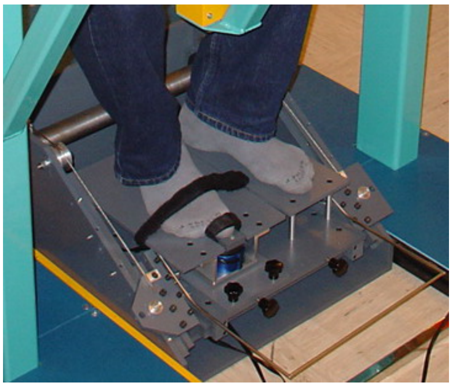

Figure 7. Mock-up in PVC of second version of the foot platform

The final version was redesigned and based on the feedbacks from the clinicians.

It is characterized by a robust structure and a very low encumbrance (the user is seated 580 [mm] above the foot platform): the two inclined walls and the whole upper structure can slide back in order to reach the position 2 (see Figure 8).

This new design makes the manufacturing simpler. The usability was also improved.

A gas spring was inserted as a counterbalance mechanism, with the aim of providing a soft movement during the change of the setting for fitting the patient size: the therapist can easily move up and down the platform in order to set the device to the proper setting.

Figure 8. The final version of the foot platform mechanical structure

IV. Technical Specifications

The functional design of the foot platform presented in this paper is illustrated in this section.

The presented foot platform is capable of measuring isometric F/T trajectories. Two 6-axis sensors are placed on the platform: one for measuring forces and torques of the foot and another for big ones.

Commercial sensors were used for this purpose (50M31A-I25 for the foot and 90M40A-I50 for the big toe, JR3 Inc., Woodland, USA). Table I shows the basic characteristics of the sensors.

Figure 9 shows the drawing of the latest version of the Foot Device. The foot platform is formed by two inclined walls on which a base platform can slide.

On the base platform two platforms are placed: one is provided with the two sensors and it allows to perform the measurements of the affected foot, the other simply supports the not affected foot.

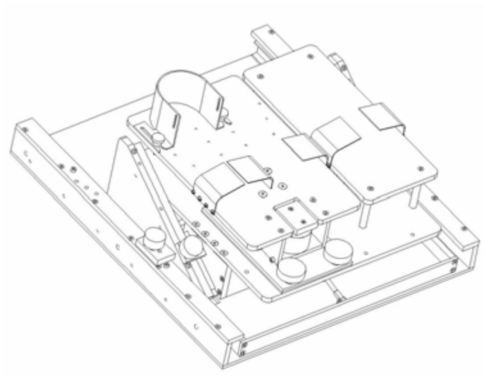

Figure 9. The foot platform

TABLE I
BASIC CHARACTERISTICS OF THE 6-AXIS F/T SENSORS

Description	N.	Lateral forces (Fx, Fy)	Axial force (Fz)	Torques (Tx,Ty, Tz)
Type-F(oot)	1	400 N	800 N	25 Nm
Type-T(oe)	1	150 N	300 N	8 Nm

The two inclined walls allows to move the base platform in order to adjust the position of the device according to the different patients sizes, maintaining the requested posture.

This objective is achieved, by pushing the base platform, up or down along the inclined walls and fixing it through the insertion of two fastener knobs, situated on the two sides of the base platform.

A gas spring counterbalances the weight of the base platform and assures a soft movement during the change of the S, M, L setting. The foot platform allows to perform measurements on both feet: a simple exchanging mechanism between the platform provided with the sensors and the platform for supporting the unimpaired foot was implemented.

The mechanism is the following: the therapist lifts the supporting platform and puts it away, unscrews two fastener knobs from the base platform, pulls the platform provided with sensors to the opposite side (from left to right or from right to left), fix it on the base platform screwing the fastener knobs and put the support platform to the empty side.

When the physiotherapist has to pass from exercises represented by the position 1 to the exercises of position 2, the foot platform must be unlocked pulling out two fastener knobs, pushed back on the horizontal rails until the relevant S, M, or L position is reached and locked through the two fastener knobs.

V. Application to Functional Assessment In Rehabilitation

The platform has been integrated into a diagnostic device (ADD, Alladin Diagnostic Device), which allows the simultaneous 8-channel recording of whole-body isometric force/torque measurements (Figure 10).

Several prototypes of the proposed foot device described in this paper have been fabricated and they are currently hosted in three different EU hospitals with the aim of evaluating a large pool of stroke patients and validating the clinical assumptions on the meaningfulness of isometric FT/ measurements in rehabilitation.

The results obtained so far show that the measurements recorded using the Foot Device capture an ADL task in a quantitative way.

Figure 11 and Figure 12 show two sample measurements of forces, recorded from a patient's foot and big toe, respectively.

Two sample measurements of torques, recorded from a patient's foot and big toe, respectively are shown in Figure 13 and Figure 14.

From the measurements collected so far, it was possible to verify that the proposed device meets the original requirements of the medical researchers, and in detail:

1) the range of forces and torques of interest for the foot and the big toe, specified by the experimental set-up, is covered by the collected measurements [12], [13];

2) the sensitivity of the sensors embedded in the platform is high enough to cater for the different anthropometric sizes and weights of the random patient population composed of more than 300 subjects all over Europe.

Furthermore, the positive feedbacks, received so far from the therapists and the patients about the performance and the overall acceptability of the proposed platform confirmed that the design and manufacturing phases have been successfully carried on.

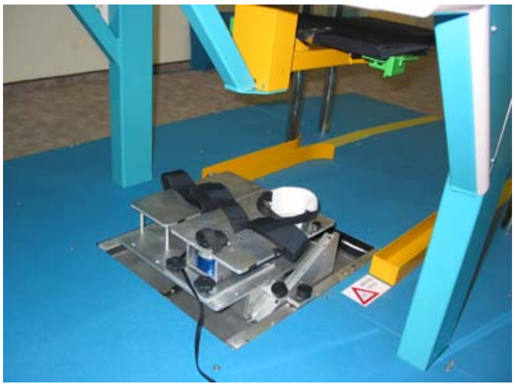

Figure 10. The foot platform integrated into the ADD (Alladin Diagnostic Device) with sensors, hell support and streps.

VI. Other Applications and Future Work

Alternative applications for the proposed platform are:

- Isometric motor exercise. Many clinical protocols for motor therapy of different type of patients prescribe the execution of isometric exercises. The proposed system could allow to accurately tune, monitor, measure and record the forces/torques exerted by the patient during such exercises. To this aim, a self-calibration routine will be added to the system, such that forces/torques due to the foot's weight will be automatically set to zero at the start of the motor therapy;
- Foot-based human-machine interface. The proposed system can be associated to a virtual reality environment for foot rehabilitation (as recently implemented with similar devices for isometric measurements in the upper limb [14]) or it can be used as novel human-machine interface for many different applications where the use of foot is required, e.g. pedal interfaces for game, surgical robots, vehicles or for enabling independent living to citizens with residual abilities in the feet.

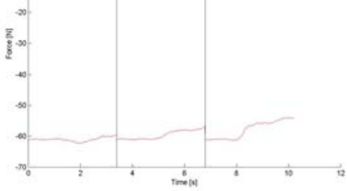

Figure 11. Sample measurement of forces (x-, y- and z- component) from the foot of a patient (three repetitions of the same exercise)

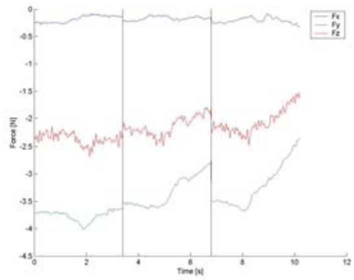

Figure 12. Sample measurement of forces (x-, y- and z- component) from the big toe of a patient (three repetitions of the same exercise)

VII. Conclusions

In this paper, a novel platform for force/torque measurements on the human foot in isometric conditions has been presented in detail, with special emphasis on the close, fruitful interaction with the medical researchers all along the development process.

The proposed platform, which is currently being validated in three different clinical centers in Europe, proved so far to be effective as a tool for experimental use in novel functional assessment procedures of post-stroke patients, according to the orginal specifications provided by the medical doctors and therapists. The platform has also a range of other potential applications, from motor therapy to foot-based human-machine interface.

The ergonomics of the device allows to have reliable and repeatable data from the foot and the big toe of a large variety of patients with different anthropometric characteristics, without requiring special effort and time consumption to the therapist for fitting the system to the different patients.

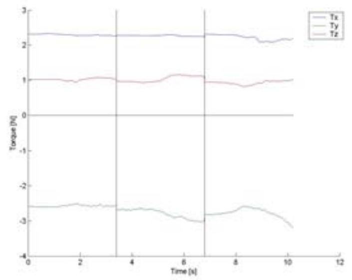

Figure 13. Sample measurement of torques (x-, y- and z- component) from the foot of a patient (three repetitions of the same exercise)

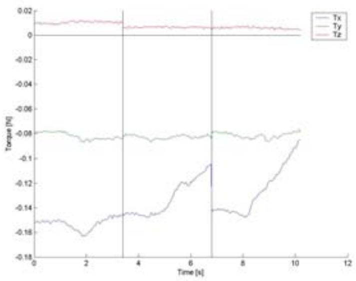

Figure 14. Sample measurement of torques (x-, y- and z- component) from the big toe of a patient (three repetitions of the same exercise)

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