ASSESSMENT OF RECOVERY AT STROKE PATIENTS BY WHOLE-BODY ISOMETRIC FORCE-TORQUE MEASUREMENTS OF FUNCTIONAL TASKS I: MECHANICAL DESIGN OF THE DEVICE

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Abstract: Evidence based neuro-rehabilitation badly needs the support of 'diagnostic precision'. This paper presents for a first time a prototype of a whole-body isometric force measurement device that grants for 'diagnostic precision' in stroke recovery. The measurement instrument is composed of eight six degrees of freedom force/torque sensors grading the performance of stroke patients during the execution of six activities of daily living (ADL). Three devices were installed in different European hospitals and have been collecting data from stroke patients since February 2005. The clinical trial will continue till July 2006, and will record clinical and biomedical data of 300 subjects.
This paper describes how the proposed diagnostic device contributes to a better understanding of the rehabilitation of stroke patients. The six selected Activities of Daily Living are defined and the mechanical design approach is presented into detail. This paper is complemented by another paper that describes the software design of the proposed isometric diagnostic device.

Introduction

Previous studies on the measurement and prediction of functional outcome in stroke mainly used coarse clinical parameters. Till now deficits being treated are rarely clearly specified and stroke patients tend to be grouped together according very broad categories of severity. As the emphasis in stroke rehabilitation is on the improvement of functional performance, an ideal measuring tool should use Activities of Daily Living tasks as a principle for its quantitative measurements. ADL tasks are well described in textbooks for physical and occupational therapists ([1], [2], [3], [4]). Because of time constrains (30 minutes measuring cycle), six tasks (Figure 1) were selected from a set of 42 possible ADL tasks. This selection was based on the analysis of similar characteristics among the total group of ADL tasks.

Figure 1: ADLs from left to right and from top to down: "drinking a glass of water", "picking up a spoon", "turning a key", "lifting a bag", "reaching for a bottle", and "bringing a bottle to the opposite side"

The ALLADIN research hypothesis states that specific force/torque features during the execution of these six functional tasks are determinants for the functional recovery of stroke patients. Moreover, these determinants should show beyond mistake neural control parameters that declare brain plasticity. Neuroscience explains how control parameters can be derived from motor imagination and initiation. The basic assumption inspiring this research work, is that imagination and initiation of the task have the same functional properties as performing the task itself [5], [6], [7], [8], [9], [10], [11], [12]. Therefore the proposed measurement device platform adopts an isometric approach for post-stroke functional assessment. Till now this knowledge has never been implemented in a measuring instrument and challenged a multidisciplinary team of European researchers whose achievements so far are partly reported in this paper.

Isometric force-torque measurement devices were extensively studied before designing the ALLADIN measuring device. Currently isometric force torque measurements are made by multifunctional isokinetic (constant angular speed) uniaxial dynamometers that simply constrain the displacement of the body part to be measured. The best known representatives of these devices are the Kin/Com and Cybex [13]. In addition, a few simple dedicated isometric devices came on to the market. These isokinetic and isometric force torque measuring devices are typically constructed for measuring the biomechanical behaviour of a single muscle or a group of muscles. Isostation B-200 and Cybex measure the trunk [14], whereas Loredan/LIDO [15] and Kin/Com measure 1 DOF muscular strength at various body parts. The Biodex – Upper Body Cycle [16] and the Norm are cycling machines that measure the muscle strength at the upper and the lower extremities respectively. Finally the Newtest Force is a product family [17] consisting of one axis isometric force measuring device for different parts of human body.

Isokinetic devices can isolate particular joints to determine the strength requirements for certain motions or the maximum voluntary contraction forces of specific muscle groups. However, confronting the specifications of the current isometric force-torque measuring devices with the ALLADIN research objectives, it appeared that the major shortcoming of the existing isometric force-torque measuring devices is that they impose artificial motions or loadings on the subject. From the biomechanical point of view, these measurements are the simplest, but provide only a little information about the underlying motor control mechanism within the body. Furthermore, unlike the current 1 DOF isometric force measurement devices, the ALLADIN objective is to capture repetitive motion imaginations and motion initiations synchronously at various body parts. This means that functional naturalness imbedded into quantitative synchronized multi channel force torque measurements, at selected body parts are key for designing the ALLADIN diagnostic device.

Materials and Methods

The proposed new device explores the sensory motor reorganization after stroke by evaluating six selected routine ADL tasks: “drinking glass of water”, “picking up a spoon”, “turning a key”, “lifting a bag”, “reaching for a bottle”, and “bringing a bottle to the opposite side”. (Figure 1) The study is spread over a period of 20 months and will measure 300 subjects altogether in the 3 centres. Each patient will be measured by the ADD 32 times in a 6 month period. Every isometric measurement is used to determine the actual status of the patient and to make comparisons possible within the same and with other patients. To make these comparisons happen, it is necessary to make the measuring device adaptable for anthropometrical differences by ensuring that each patient starts from the same anatomical position. Only this guarantees an inter and intra reliability.

In all the six tasks the patient occupies a comfortable sitting posture, whereas the position of the trunk, the arm, and the leg varies from task to task. The first design task had to answer following questions: 1) which body part to measure, 2) which type of Force Torque sensors, 3) how to handle the patient in the measurement device, 4) how to adapt the device to the anthropometrical differences between the patients while to keep a standardized measurement position and protocol

To obtain the most accurate picture of the isometric forces produced during motion imagination and motion initiation at all body parts, it was decided to have force-torque sensors behind the trunk, below the posterior, at the affected lower arm, at the affected thumb, index finger, and middle finger, at the affected foot and toe (Figure 2). The sensors are located as such that each of them can deliver supplementary and complementary information on the motor representation in the brain of the ‘forward model’ of the respectively task. The behaviour of the patient is then the combined output of all parameters registered by all sensors during all proposed tasks.

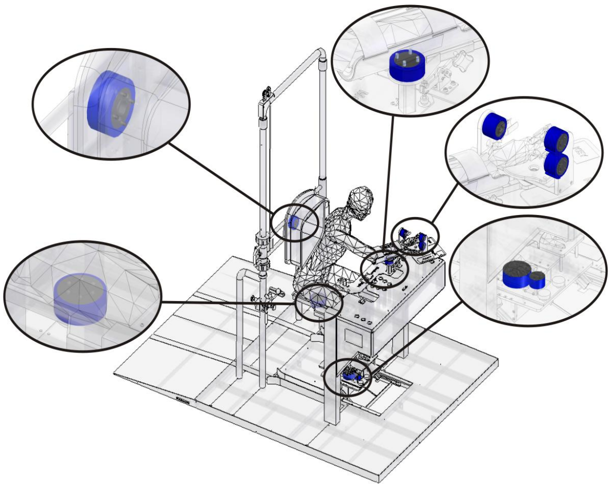

Figure 2: The ALLADIN Diagnostic Device uses 8 6 DOFs force-torque sensors for the isometric force measurement of repetitive ADLs

Because the analysis requires both the 3D forces and 3D torques exerted by the patient it was decided to use 6 DOF force-torque sensors in the ALLADIN Diagnostic Device (ADD). These transducers are the most sophisticated parts and measure force along and torque around the axes of an orthogonal co-ordinate system. The sampling rate was set at 100 Hz, and the resolution to be 0.1 N or better, which is acceptable for the analysis of isometric force records of stroke patients. The nominal measuring ranges of the eight sensors were all defined separately, as this feature depends on the location and orientation of the sensor, as well as on the loading exerted by the measured body part. Literature data [18], [19], [20], [21], [22], and also preliminary measurements [23], were used for the final specification of the nominal measuring range. Table 1 shows the parameters of the sensors selected from the product assortment of JR3 Inc.

Table 1: Nominal measuring ranges of the 6 DOFs force-torque sensors built into the measuring device

Measured body part	Lateral forces (F_x, F_y)	Axial force (F_z)	Torques (T_x, T_y, T_z)
Thumb	150 N	300 N	8 Nm
Index finger	150 N	300 N	8 Nm
Middle finger	150 N	300 N	8 Nm
Lower arm	150 N	200 N	10 Nm
Trunk	250 N	250 N	20 Nm
Posterior	550 N	550 N	50 Nm
Foot	400 N	800 N	25 Nm
Big toe	150 N	300 N	8 Nm

The suggested isometric force measurement requires fixed, anatomically standard, and individual setting of the device for all patients. As patient dimensions vary over significant ranges, only a computer controlled positioning system can 100% satisfy these three requirements together without error. However the price and the complexity of such a device would limit a possible exploitation seen its extremely high cost. For example, 3 axes at the foot, 3 axes at the arm, and 3x3 axes at the three fingers should have been positioned in the case of a patient fixed to a seat. In contrast with this expensive solution the ALLADIN research team decided to build a simple mechanically adjustable, discrete setting isometric force measurement device. To define the ideal number and range of the discrete settings the anthropometrical data of the European population was studied [24], [25] and it was decided to implement three discrete settings for the percentile values of the 25%-ile female, the mean of the 50%-ile male and female, and the 75%-ile male. This means that the ADD can be set without error only to the 25%-ile female, the mean of the 50%-ile male and female, and the 75%-ile male. For that reason patients larger than the 95%-ile male or smaller than the 5%-ile female are excluded from the study. The detailed design of the ADD was performed in CAD systems Pro/Engineer, SolidEdge, and Autodesk Inventor. The 3D mannequin models were created with using the Mannequin Pro tool [8], and inserted into the CAD environment. The anthropometrical settings were optimised and also colour coded for the S, M, and L patient sizes (Table 2). Figure 3 shows the female (25 and 50%-ile) and male mannequins (50 and 75%-ile) set for the ADL task ‘lifting the bag’. The same figure also illustrates how the anthropometrical design approach was translated to various fixture sizes in the ADD. The ultimate result of the adopted anthropometrical design is the fixed set of anatomical angles in the three functional positions (Table 3) for any patient size. The calculated deviation from the ideal anatomical angles remains in the range of ±0.5°.

Table 2: Definition of the patient size in ALLADIN

Label	Colour code	Height
S	Yellow	1530 – 1625 [mm]
M	Green	1625 – 1751 [mm]
L	Blue	1751 – 1870 [mm]

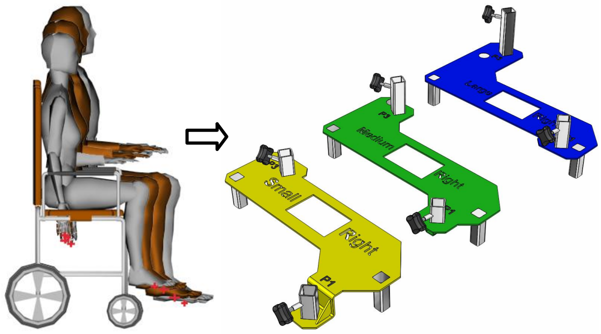

Figure 3: The anthropometrical differences are handled with simple mechanical adjustments and fixture sets

Table 3: Anatomical angles are standardised in the three functional positions

Anatomical angle	ADL1, ADL2, ADL3	ADL4	ADL5, ADL6
Shoulder abduction	15°	5°	5°
Shoulder flexion	50°	-7°	100°
Shoulder internal rotation	45°	0°	45°
Elbow flexion	35°	12°	20°
Thumb abduction	50°	50°	50°
Finger metacarpophalangeal flexion	15°	15°	15°
Finger proximal interphalangeal flexion	20°	20°	20°
Finger distal interphalangeal flexion	20°	20°	20°
Lumbar-thoracic flexion	0°	0°	30°
Lumbar-thoracic rotation	0°	0°	20°
Lumbar-thoracic lateral flexion	0°	0°	18°
Hip flexion	90°	90°	90°
Knee flexion	90°	90°	110°
Ankle dorsiflexion	0°	0°	8°
Toe metatarsophalangeal flexion	0°	0°	7°

The ergonomic design of the ADD helps the physiotherapist in moving the patient from the wheel-

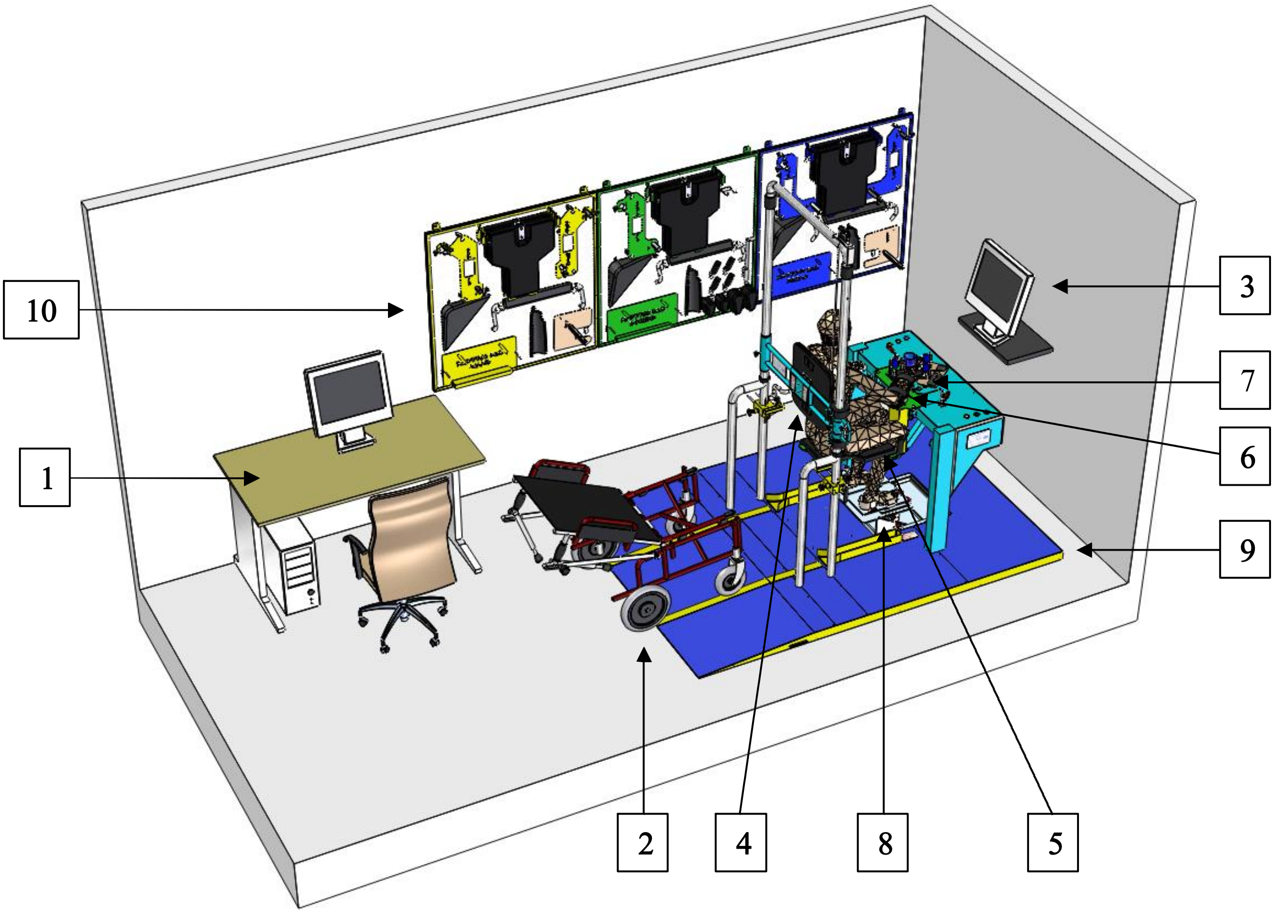

Figure 4: The ALLADIN Diagnostic Device includes the following main units: control and data acquisition workstation (1), transit lying wheelchair (2), monitor for the patient (3), trunk device (4), seat device (5), arm device (6), finger device (7), foot device (8), frame (9), accessory storage board (10).

chair to the ADD and set him/her for each ADLs easily. A survey of commercially available wheelchairs showed that a special standard lying wheelchair was available having features that make the transfer of the patient to the ADD very straightforward. Figure 4 illustrates the final design of the ALLADIN Diagnostic Device set for ADL task 1: “drinking a glass of water”. The ADD is a class I medical device with measuring function. The relevant standards, and safety requirements stipulated

Figure 5: The ALLADIN Finger Device integrated with the ALLADIN Arm Device

Figure 6: The ALLADIN Foot Device

by the Medical Device Directive 93/42/EEC were considered in the design and development.

In an iterative development approach from June till November 2004, three prototype devices were produced, assessed by the clinical experts, and improved. The final version of the ALLADIN Diagnostic Device (Figure 4) consists of five main functional units: the Finger device (Figure 5), the Arm device (Figure 5), the Foot device (Figure 6), the Trunk device (Figure 7), and the Seat device (Figure 8).

Figure 7: The ALLADIN Trunk Device

Figure 8: The ALLADIN Seat Device

Results

Three diagnostic devices were delivered and installed respectively at the Maria Middelares Hospital (Gent, Belgium, Figure 9), in the Adelaide & Meath and the National Children Hospital (Dublin, Ireland), and in the Szent Janos Hospital (Budapest, Hungary). The first results of the clinical trial are now available.

Figure 9: Isometric force-torque measurement in progress in the Maria Middelares Hospital

Till the 30th of August 2005 28000 force torque measurement records were collected. A few complete datasets are available for data mining. All the three ALLADIN Diagnostic Devices have been found reliable under a workload of 6-8 hours a day.

Discussion

A companion EMBEC 2005 paper reports the work on the development of the software tools embedded in the ALLADIN Diagnostic Device.

The scope of the current paper was not the review of the measurement results but a thorough description of the measuring device and its objectives. The data themselves will follow a strict procedure of manual and statistical pre-processing and will finally examined by special designed data mining approach that show the relationship between the force-torque characteristics during the performance of the functional tasks and the recovery track of stroke patients.

A preliminary study shows that at least four groups of parameters can be extracted from the records. These are parameters describing: 1) the 'force recruitment' during movement initiation (Figure 10, 11), 2) the trajectories of the 3D direction of the resultant force, 3) the functional delays across the different body parts, 4) the 'rest force'.

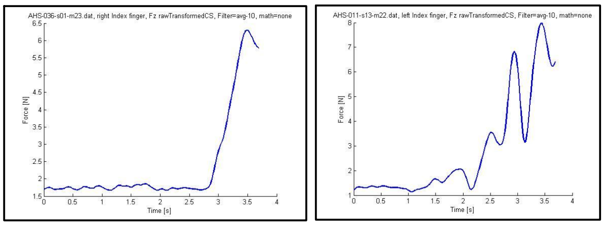

Figure 10: Normal and abnormal patterns in ADL1. Determination of the starting point is difficult.

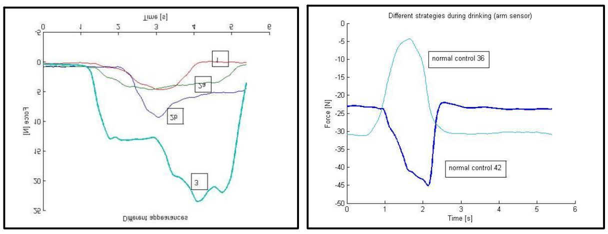

Figure 11: Examples on different reaction (left) and different motor control strategies

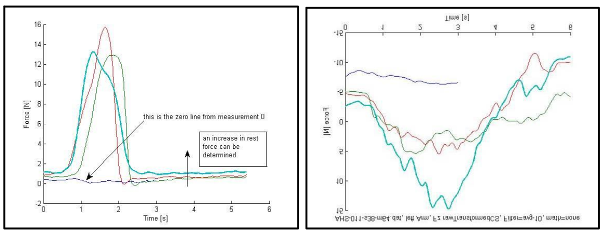

Figure 12: Rest force at normal control (left) and at patient. Increase of the rest force can characterize spasticity.

Conclusions

In this paper, the mechanical design of the novel ALLADIN Diagnostic Device for post-stroke functional assessment was presented. The system is the first tool provided to neuro-rehabilitators for whole-body isometric measurements. The device provides accurate and repeatable measurement results for stroke patients thanks to a precise mechanical positioning and fixation system for each task to be performed.

Preliminary experimental testing demonstrated the feasibility of the proposed scientific objectives, namely to extract quantitative markers on the integrity of nervous system in post-stroke patients..

Acknowledgement

This work was supported by the ALLADIN European project. The experiments comply with the national laws and local ethical committees.

This work was partly supported by the European Commission - 6th Framework Programme under the grant N. 507424 (ALLADIN – Natural Language Based Decision Support in Neuro-rehabilitation). The authors are members of the ALLADIN consortium. The other partners of the ALLADIN project are: Language and Computing NV (Belgium), Zenon SA Robotics and Informatics (Greece), University of Wales Cardiff (UK), and Multitel ASBL (Belgium)

Special thank goes to all other project members.

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