25th ABCM International Congress of Mechanical Engineering
October 20-25, 2019, Uberlândia, MG, Brazil

# DESIGN FOR ASSISTIVE TECHNOLOGY: DEVELOPMENT OF AN UPPER LIMBS EQUIPMENT FOR REABILITATION

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***Abstract:*** *The objective of this paper it to propose a design engineering procedure for development of assistive device using a case study focused on upper limb equipment to therapeutics and rehabilitation activities for people affected by CVA. The abandonment is an important consideration of engineering design and clinical studies important function of the multifactorial knowledge. There is a large orthosis' variety to assist the upper limbs movement; however, few of those devices are focused on the cerebral vascular accident (CVA) rehabilitation. In addition, almost all devices are imported products and reach the Brazilian market having a high added value. Considering the rehabilitation centers' importance, which are included in the Brazilian public health system and normally work with a short financial budget, it is interesting to develop a rehabilitation device to meet the Brazilian demands. The design for assistive technology can be an interface of the engineering-AT to offer constructive solutions that minimize the abandonment during and after therapeutics and rehabilitation activities. In this context, the design methodology offers innovation opportunities and multidisciplinary communication, mainly in early phase of the design development.*

***Keywords:*** *orthosis, co-participatory design; design method; disability; exercise therapy.*

## 1. INTRODUCTION

Assistive Technology (AT) is the health area that prescribes devices, methods, and services to support disabled individuals in order to promote autonomy gains for a higher life quality (CAT, 2009). The assistive device development has two main objectives: to offer therapeutics' treatment and to offer rehabilitation activities to improve autonomy and movement performance. Subjects' needs, preferences, abilities, limitations, and even their environments should be carefully considered to ensure the AT success (Enderle and Bronzino, 2012).

In practice, many ATs do not pass through a proper development process which results in a large number of abandonments. According to Plos *et al.* (2012), about 1/3 of the assistive devices are abandoned, some after three months, others after five years of use. Philips and Zhao (1993) *apud* Cruz *et al.* (2016) identified four factors related to assistive devices abandonment: (a) not considering users' opinions; (b) easy device acquisition; (c) poor device performance; and (d) changes in users' priorities.

To avoid this scenario, users-centered design (UCD) methods have shown that including users' perspectives during the AT design enables device development for suiting the users' needs better (Abras, Maloney-Krichmar and Preece, 2004). Assistive devices are normally products customized or on-demand and they are best designed if the designing team can understand the users' language, as healthcare professionals do, and can generate a product that considers the technical reliability, managed by the engineers. The users' inclusion (end-users, occupational therapists, physiotherapists, family, and caregivers) are also fundamental in the co-participatory/co-creation design phases; "which means involving them iteratively and bidirectionally on the design in early stages" (Hu, 2013).

The main contribution of the AT-engineering interface is to offer secure solutions that minimize the abandonment during and after therapeutics activities. In that context, the design methodology can offer innovation opportunities and multidisciplinary communication. Although there are different designing methodology procedures which help adapting to each problem, there are no specific guidelines for assistive devices. This paper proposes a designing procedure for the early stages (informational and conceptual phase) of assistive devices' development. The case study aims to show the steps to build the conceptual solution of an equipment to use in therapeutic and rehabilitation activities for stroke survivors' upper limbs.

## 2. CASE STUDY

Encephalovascular diseases, including CVA, are the third cause of physical incapacity in the world. After a stroke, the person generally presents musculoskeletal residual disability or sensory and cognitive alterations, which may affect the upper limbs, limiting as well as slowing their movement range (Raimundo *et al.*, 2011). "Among the problems caused by stroke, hemiparesis on the lesion contralateral side is very frequent and could be responsible for muscle weakness or partial motor paralysis in a hemibody. Hemiparesis can lead to upper limb motor impairments, causing deficits in motion range and arm power lack to reach and hold, leading to dependence during daily activities course" (Rodrigues, 2016).

Upper extremity function recovery is one of the primary goals of rehabilitation programs. About 40% of occupational therapies are directly targeted at improving activities of daily living (ADL). Several studies have shown that focusing on daily functional activities is vital in stimulating motor recovery after stroke (van Ommeren et al., 2018). For those individuals, repetitive movement therapy with robots has shown to be promising. However, the robotic devices are quite expensive and are currently limited in terms of therapy routine (Iwamuro *et al.*, 2008).

As an alternative, it is interesting to use a passive device to assist arm movement training guided by a therapist. By simply supporting the arm weight, stroke survivor reaching power is increased because there are shoulder torque reductions (Iwamuro *et al.*, 2008). By improving the user's reaching capabilities, the device could enable the performance of task-specific training movements that would not be possible otherwise.

There are many kinds of devices for the upper limb physical therapy (Maciejasz *et al.*, 2014); however, few of them have been clinically tested (Balasubramanian, Klein and Burdet, 2010); therefore, health professionals do not encourage the use of the untested ones. Besides, in Brazil, most of those products that reach the market are imported and have a high value due to taxes. Considering the rehabilitation centers' importance, which are included in the Brazilian public health system and normally work with a short financial budget, it is interesting to develop a rehabilitation device to meet the Brazilian needs.

## 3. PROPOSED DESIGN PROCEDURE

The design procedure focused in the Informational and Conceptual phases. Its tasks are presented through the flowchart in the Figure 1.

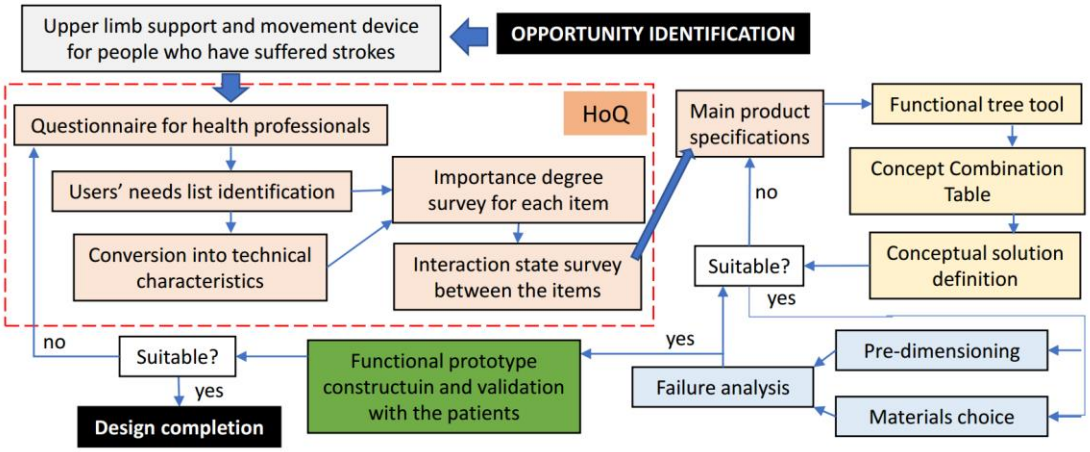



Figure 1. Flowchart of the steps performed for the upper limbs support and movement device design.

The study target or end-users were adults ranging from 20 to 65 years old affected by stroke. However, the control group interviewed to collect this work data was composed by six occupational therapists experienced in the use of upper limb support and movement devices. As those professionals indicate and assist the equipment uses with the end-users, they understand the limitations of existing products and they are capable to express the users' needs. The multidisciplinary designing team which led the work was composed by mechanical engineers and occupational therapists. This work was accepted by the Informed Consent of the public ethics committee in Brazil (CAAE number 30908114.0.0000) The project is available in *Plataforma Brasil*.

### 3.1 Informational phase: identifying users' needs and product specifications

The philosophy behind the users-center design method (UCD) is to create a high-quality information channel that runs directly between customers in the target market and the product developers (Ulrich and Eppinger, 2004). For

that, it is necessary to gather and interpret the raw data from customers. In this work, the control group answered a questionnaire in order to obtain the raw data of the users' needs, which was categorized and listed in items as shown in Table 1. Then, a multiple-choice questionnaire was answered by that control group to establish the importance level those items, as also shown in Table 1.

Table 1. Description of the users' needs and their importance.

| Users' needs | Description | Importance (1) | | | Average |
|---|---|---|---|---|---|
| | | 9 | 3 | 1 | |
| Bilateral | Unilateral or bilateral support and movement | ••• | ••• | | 6 |
| Flexibility | Equipment use with different furniture types (for example, hospital bed and wheelchair). | ••••• | • | | 8 |
| Quick Assembly | Fitting parts easily to use. | •• | ••• | • | 4.7 |
| Patient Weight | Ability to support members without device deformation. | ••••• | • | | 8 |
| Material Resistance | Ability to maintain the material original, without damage after use. | •••• | •• | | 7 |
| Comfort | Device with cosiness. | •••••• | | | 9 |
| Sanitation | Cleanable parts. | ••• | • | •• | 5.3 |
| Forearm Support | Component design that is in contact with the suspension arm. | •• | ••• | • | 4.7 |
| Hand Stabilization | Component design that is in contact with the suspended hand. | ••• | • | •• | 5.3 |
| Height Adjustment | Possibility of adjusting the height according to users' demands. | •••• | •• | | 7 |
| Easy Storage | Easy to keep. | • | •••• | • | 3.7 |
| Easy Disassembling | Easy to separate parts. | ••• | • | •• | 5.3 |
| Low Price | Low in-store acquisition cost. | •••• | • | • | 6.7 |

(1) Importance level of users' needs established by the control group (six occupational therapists) as very important (9 points), important (3 points) and less important (1 point).

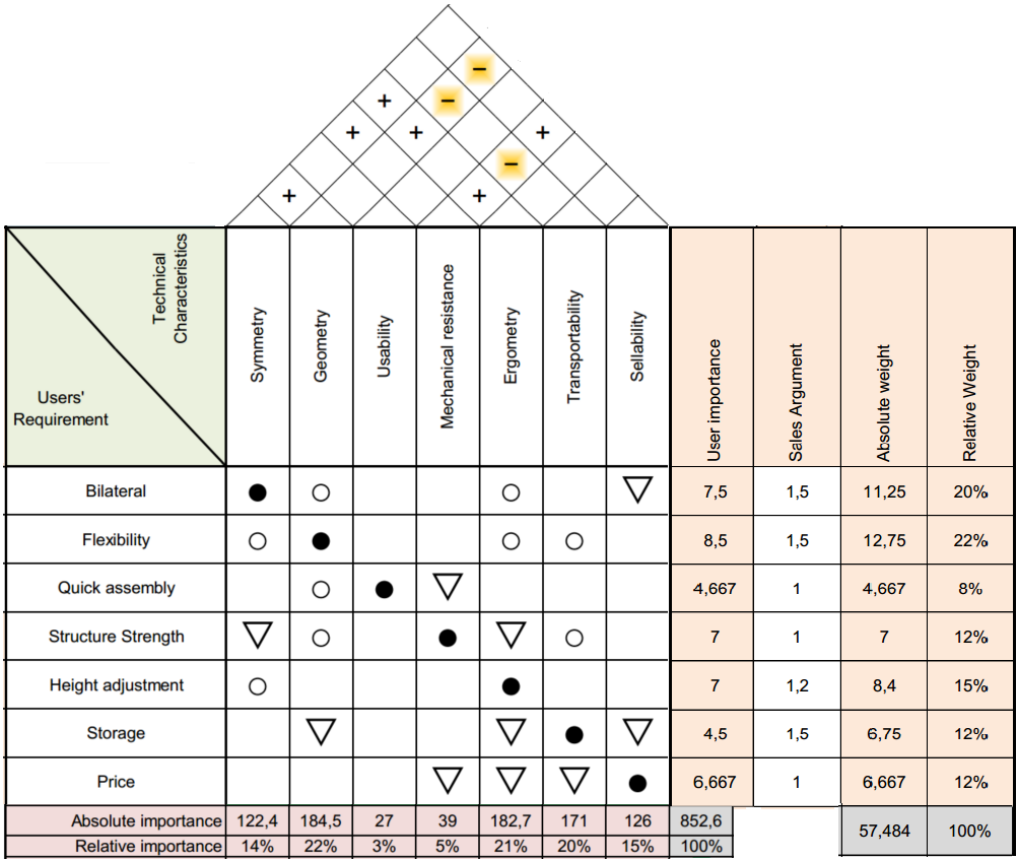
The users' requirements are the set of users' needs refined and grouped by parity and similarity; the implied needs are not considered. That way, the designing team decreases the items to be observed and allocates resources in more important items. Users' needs are also expressed in the "language of the customer". Those expressions are helpful to develop a clear sense of interest to customers, but they fail to provide specific guidance on how to design and engineer the product (Ulrich and Eppinger, 2004). For that reason, the users' needs were translated into technical characteristics in order to give a reference measure that fits those users' needs. Table 2 shows the conversion of users' needs into technical characteristics.

Table 2. Development of users' needs for technical characteristics.

| Users' needs | Users' Requirements | Technical Characteristics | Description | Reference Measure |
|---|---|---|---|---|
| Bilateral + Comfort | Bilateral | Symmetry | Structure external dimension. | [m] |
| | | | Arms' workspace. | [$m^3$] |
| Flexibility + Comfort | Flexibility | Geometry | Dimension suitable to fit with other furniture. | [m] |
| | | | Volume suitable to transit inside hospitals/home. | [$m^3$] |
| Quick Assembly | Quick Assembly | Usability | Low operation time to assembly. | [s] |
| Material Resistance | Structure Strength | Mechanical resistance | Material choice to avoid corrosion | Unit |
| | | | Resistance to buckling | [MPa] |
| | | | Resistance in supporting patient's weight | [MPa] |
| Height Adjustment | Height adjustment | Ergometry | Standard ergonomic dimensions | [m] |
| Easy to Store | Storage | Transportability | Packing index | [%] |
| Easy to Disassemble | | | | |
| Price | Price | Sell-ability | Low price | [$] |

A graphical tool named Quality Function Deployment (QFD) supports the designing team's discussion and decision making by providing a way to represent the product specifications. In the House of Quality matrix (HoQ), the designing team defined the relationship between users' requirements and technical characteristics, based on the information collected from the questionnaire, as shown in Figure 2. In addition, including the information on competing products and the sales' argument level of the users' requirements, the HoQ matrix calculates the relative importance of each product specification.

In this work, the main users' requirements raised by the HoQ matrix were flexibility (22%), bilateral (20%), and height adjustment (15%); also, the main technical characteristics were geometry (22%), ergonomics (21%), and transportability (20%). In other words, that design should provide its use in different furniture types, for one or both arms, having ergonomic adjustments (mainly, the height fitting), with a comfortable structure, and compatibility to hospital and house environments. An important aspect to be emphasized is that for storing the device needs to be as small as possible. In general, in public Brazilian rehabilitation centers, therapists work with several patients in the same medium-sized room. If the device takes up too much space, it might impair the occupational therapist session dynamics.



| Users' Requirement \ Technical Characteristics | Symmetry | Geometry | Usability | Mechanical resistance | Ergometry | Transportability | Sellability | User importance | Sales Argument | Absolute weight | Relative Weight |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Bilateral | ● | ○ | | | ○ | | ▽ | 7,5 | 1,5 | 11,25 | 20% |
| Flexibility | ○ | ● | | | ○ | ○ | | 8,5 | 1,5 | 12,75 | 22% |
| Quick assembly | | ○ | ● | ▽ | | | | 4,667 | 1 | 4,667 | 8% |
| Structure Strength | ▽ | ○ | | ● | ▽ | ○ | | 7 | 1 | 7 | 12% |
| Height adjustment | ○ | | | | ● | | | 7 | 1,2 | 8,4 | 15% |
| Storage | | ▽ | | | ▽ | ● | ▽ | 4,5 | 1,5 | 6,75 | 12% |
| Price | | | | ▽ | ▽ | ▽ | ● | 6,667 | 1 | 6,667 | 12% |
| Absolute importance | 122,4 | 184,5 | 27 | 39 | 182,7 | 171 | 126 | 852,6 | | 57,484 | 100% |
| Relative importance | 14% | 22% | 3% | 5% | 21% | 20% | 15% | 100% | | | |

Figure 2. House of Quality (HoQ) developed to assistive equipment for upper limb movement.

### 3.2 Conceptual phase: concept generation and selection

A product concept is an approximate description of technology, working principles, and product form; that is, a concise description of how the product will satisfy the users' needs (Ulrich and Eppinger, 2004). In order to form the concept by the designing team, a Functional Tree, which is a tool to describe the device operations through functions free of any technical solutions, was used. Figure 3 shows that functional tree. In the sequence, the elected functions served as input to a tool named Concept Combination Table which was the way used to join technical solutions. For each designing function, the designing team proposed several possible technical solutions, as shown in Figure 4.

Potential conceptual configurations to the overall problem are formed by combining the chosen technical solution in one line to the others in the matrix. The designing team choose two conceptual device configurations with different technical solutions, as shown in Figure 4, in order to compare them through the Evaluation Solution Variants technique. Furthermore, mock-ups of those two configurations were built to facilitate the interaction between the designing team and the health professionals for the comparison of which configuration is most interesting. Figure 5 shows the 3D model of those configurations. After having those small-scale physical models, it was possible to simulate

how to assembly the device to apply it to the patient. The information collected from the mock-ups was very rich because users could show their satisfaction or dissatisfaction with the product subsets.

Pahl *et al.* (2013) suggests a tree named Evaluating Solution Variants as a technique for comparing conceptual configurations, where designing objectives are defined and subdivided in a hierarchical order to decrease complexity levels until they reach measurable objectives that, when combined, meet the users' needs, as shown in Figure 6. The relevance of the evaluation criteria is established by the "weighting factors" of the objectives, that means, the relative importance of each objective in its level, shown in percentages (number between 0 and 1). Figure 7 illustrates the tree of objectives with their respective weighting factors. The number on the left of the balloon represents the objective weighting factor (w) which is just related to its level and tree segment and the number on the right represents the objective global weighting factor (gw). The Eq. (1) shows an example how to calculate the global weighting factor.

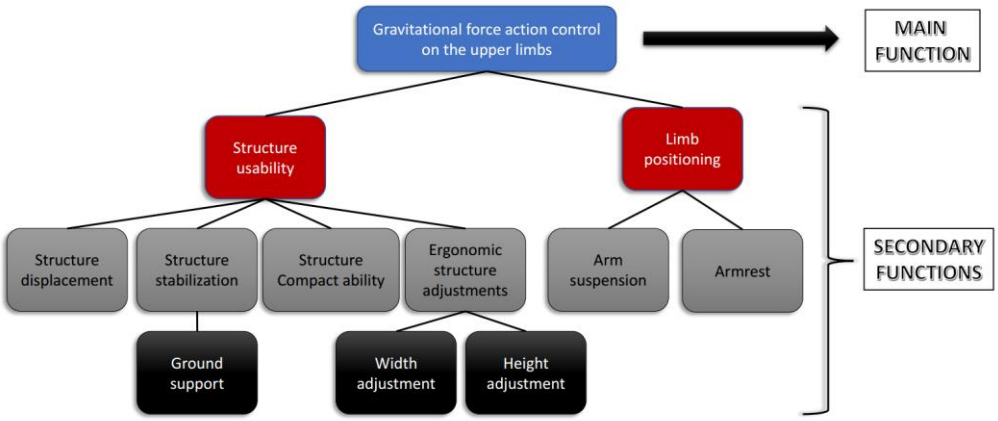



Figure 3. Upper limbs support and movement device's Functional Tree.

| Design functions | Technical solutions | | | |
|---|---|---|---|---|
| **Structucture displacement** | Rotating caster | Rotating caster with locker | Caster with swivel controlled by the user | Rubberized cylinder |
| **Ground support** | Single U-shaped base | Base with T format | Base with parallel bars | Tripod |
| **Structure compactability** | Telescopic system | Structure folds at its medial point | Structure that folds more then once | |
| **Width adjustment** | Telescopic system | Longitudinal bearing | Fixed but suitable dimensions for doors and car spaces | |
| **Height adjustment** | Telescopic system | Power screw | Fine adjustment on the arm suspension | |
| **Arm suspension** | Counterweight system | Steel cable and springs system | | |
| **Arm rest** | Band in 8 (wrist-elbow support) | Elastic band (forearm support) | Crib for the arm | Band in 8 and gove combination (wrist-elbow support) |

Configuration (2) Configuration (1)

Figure 4. Concept Combination Table for the upper limbs support and movement device.

After establishing the evaluation criteria (the objectives) and defining their relevance, the designing team defined the parameters magnitude for each criterion in the conceptual device of both conceptual device configurations, as shown in Table 3. As this project was developed until the conceptual phase, many parameters were compared qualitatively. For a more precise analysis, it is necessary to build a functional prototype to compare factors such as assembly time (s), manufacturing price, and materials choice (R$). Other factors, such as volume ($m^3$), base area ($m^2$), and weight (kg), were determined by the 3D-CAD model.

In order to establish a scale to compare the same parameter between the conceptual device configurations, a value between 0 and 10 was chosen to represent which configuration best meets the evaluation criterion (10 being the maximum value). Thus, the configuration that best meets the evaluation criteria was decided the higher sum of the weighed scores, as shown in Eq. (2). As shown in Table 4, the conceptual device configuration that best meets the evaluation criteria was the configuration 2. Therefore, this was the configurations chosen for sequencing in the next

design phases. Due to the innovative content of the concept configurations, compared to existing products in the market, the work resulted in the deposit of an invention model patent BR 1020170023052 (Cavalcanti, *et al.*, 2017).

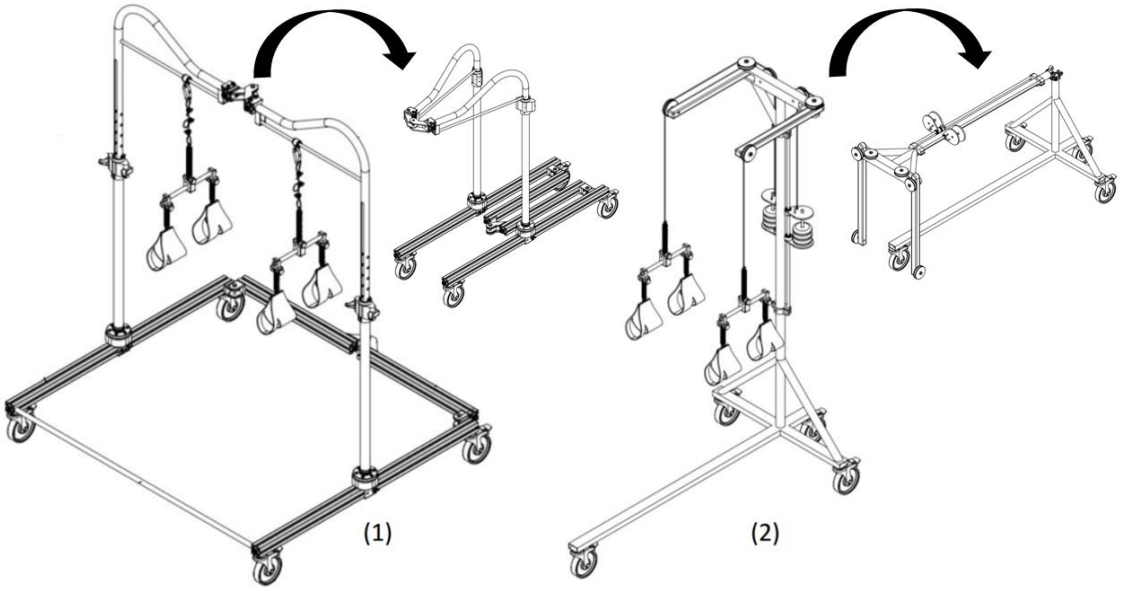



Figure 5. Two options of conceptual device configuration for the upper limb support and movements device.

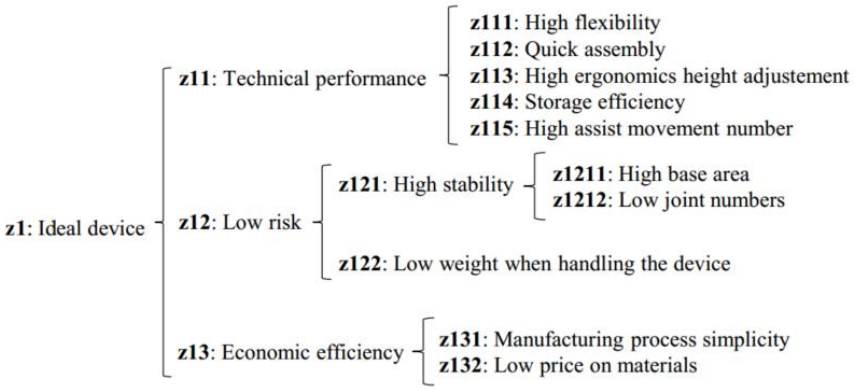



Figure 6. Evaluation Solution Variants: objectives tree of the upper limb support and movements device.

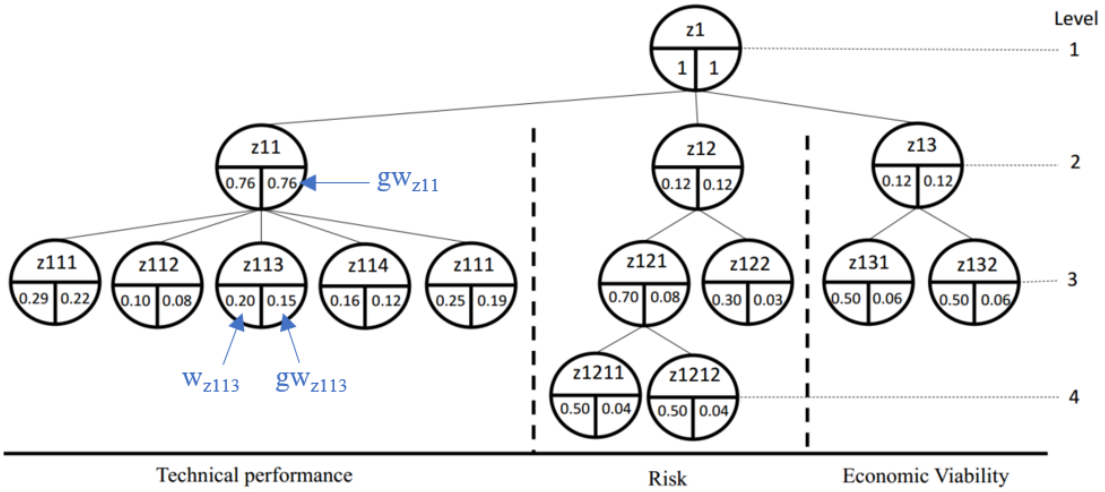



Figure 7. Objectives tree with weighting factors.

$$gw_{z113} = w_{z113}.gw_{z11} \quad (1)$$

where
$gw_{z11}$ is the global weighting factor of the $z_{11}$ item
$w_{z113}$ is the weighting fact of the $z_{113}$ item
$gw_{z113}$ is the global weighting factor of the $z_{113}$ item

Table 3. Parameters magnitude for the conceptual device configurations.

| Evaluation criteria | Parameters | Unit | Configuration 1 | | Configuration 2 | |
|---|---|---|---|---|---|---|
| | | | Magnitude | Value | Magnitude | Value |
| **High flexibility** | Amount of furniture the device adapts to. | un. | 4 (Chairs, armchairs, wheelchairs and hospital beds.) | 10.00 | 3 (Chairs, armchairs and wheelchairs) | 7.50 |
| **Quick assembly** | Amount of adjustments to be done when assembling the device. | un. | 4 | 2.50 | 1 | 10.00 |
| **Ergonomics height adjustment** | Range of height in the device's structure. | mm | 255.0 | 10.00 | 200.0 | 7.84 |
| **Storage efficiency** | Minimal volume to store the device. | $m^3$ | 0.809 | 9.60 | 0.778 | 10.00 |
| **High assist movement number** | Amount of arm movements the device assists. | un. | 2 (Shoulder: partially assists flexion/extension and abduction/adduction movements. Elbow: assists flexion/extension movements) | 6.67 | 3 (Shoulder: assists flexion/extension and abduction/adduction movements. Elbow: assists flexion/extension movements) | 10.00 |
| **High base area** | Maximum base area | $m^2$ | 1.843 | 10.00 | 0.980 | 5.32 |
| **Low joint numbers** | Minimum number of joints | un. | 8 | 3,75 | 3 | 10.00 |
| **Low weight when handling the device** | Minimum weight to handle the device. | kg | 17.729 | 5.59 | 9.903 | 10.00 |
| **Manufacturing process simplicity** | Number of parts that have a higher complexity degree at machining | un. | 8 | 10.00 | 11 | 7.27 |

Table 4. Correlation matrix of evaluation criteria and parameters.

| Evaluation criteria | gw | Configuration 1 | | Configuration 2 | |
|---|---|---|---|---|---|
| | | Value | Weighted Value | Value | Weighted Value |
| **High flexibility** | 0.22 | 10.00 | 2.2 | 7.50 | 1.65 |
| **Quick assembly** | 0.08 | 2.50 | 0.2 | 10.00 | 0.8 |
| **Ergonomics height adjustment** | 0.15 | 10.00 | 1.5 | 7.84 | 1.176 |
| **Storage efficiency** | 0.12 | 9.60 | 1.152 | 10.00 | 1.2 |
| **High assist movement number** | 0.19 | 6.67 | 1.2673 | 10.00 | 1.9 |
| **High base area** | 0.04 | 10.00 | 0.4 | 5.32 | 0.2128 |
| **Low joint numbers** | 0.04 | 3,75 | 0.15 | 10.00 | 0.4 |
| **Low charge when handling the device** | 0.03 | 5.59 | 0.1677 | 10.00 | 0.3 |
| **Simplicity in the manufacturing process** | 0.06 | 10.00 | 0.6 | 7.27 | 0.436 |
| | | TOTAL: | 7.637 | TOTAL: | 8.075 |

$$S_j = \sum_{i=1}^{n} r_{ij}\ gw_i \tag{2}$$

where
$r_{ji}$ = the value of configuration *j* for the *i*th evaluation criteria
$gw_i$ = the global weighting factor for *i*th evaluation criteria
n = number of the evaluation criteria
$S_j$ = total score for configuration *j*

## 4. DISCUSSION

The users-centered design (UCD) method is a way of considering the users' needs in the design's decision making. The direct involvement of users provides important guidance during the design process towards user-friendly and effective products (Bühler, 1996). In AT area, the users' perspective is crucial since patient contentment is related to quality of care, which is related to treatment efficacy versus abandonment rate (Bettoni, et al., 2016). There are different ways to gather the raw data from users, such as interviews, observation of users' interaction with the product, among others. However, in this work, the designing team chose to apply two questionnaires to the control group (six occupational therapists) in order to obtain the users' needs and establish their importance level in the upper limb support and movement device design. Thus, the data were obtained quickly and the importance level of each users' needs were given directly by the users.

The interpretation of those data was crucial for the next design steps, so several rounds of brainstorming were carried out between the designing team to discuss what product specifications best met the users' needs. The fact that the designing team was composed with occupational therapists and mechanical engineers helped understanding and transcribing the users' needs into technical engineering terms. The designing team also stipulated the relationship between the product specifications and drew up a market strategy, that is, chose the specifications that would have greater sales argument though analisys of competing products. Those information were inserted in the HoQ tool, which indicated the product specifications that should be priority in the device development.

The users' needs list and the preliminary product specifications were the inputs to the concept generation process. The product concept is developed to solve a problem, usually complex, and it must be decomposed into simpler subproblems to facilitate the designing team vision. In this work, the designing team used the functional decomposition approach through the Functional Tree tool. In other words, the designing team divide the problem of support and movement of the upper limbs for individuals who suffered stroke into several distinct subfunctions in order to facilitate comparison and pruning, based on HoQ results.

Used in conjunction with the Functional Tree tool, the Concept Combination Table provides a way to consider combinations of solution fragments systematically (Ulrich and Eppinger, 2004). From this moment the product physical concept began to be developed. The designing team researched several technical solutions to accomplish each of the previously defined subfunctions. Therefore, the functions should be clearly defined, so the engineers can suggest appropriate solutions to the problem. The physical concept was conceived by choosing a technical solution for each function. The designing team used criteria of advantages and disadvantages besides choosing the technical solutions that are compatible with each other. It is recommended that the most important functions according to the HoQ result are chosen first and the other functions should fit into them: the function "structure compactability" was related to "flexibility" (22%) and "geometry (22%); the function "height adjustment" was related to "ergometry" (21%) and "height adjustment" (15%); the function "structure displacement" was related to "transportability" (20%); and the functions "arm suspension" and "arm rest" were related to "bilateral" (20%).

To ensure that the set of technical solutions chosen was in fact the best option, two possible conceptual device configurations were chosen to be analyzes through the Evaluating Solution Variants technique. This technique involves the definition of parameters essential to the product, usually related to technical performance, possible risk in the product uses, and economic viability. Each parameter had a different influence on the project, so the designing team assigned the weighting factors based on HoQ results, shown in Figure 7. The comparison between the parameters was performed to the two chosen conceptual device configurations, and many parameters were compared quantitatively (like volume, weight, among other dimensions), but other parameters had to be compared in a qualitative way. Furthermore, parameters such "quick assembly", "high stability", and "economic efficiency", were poorly compared. For a more accurate evaluation it is necessary the construction of a functional prototype.

Although some parameters were not ideally compared, the Evaluating Solution Variants technique pointed to the conceptual device configuration that best meets the users' needs and the basic design requirements. This configuration will be carried out in the next design stages, which involve pre-sizing, material selection and failure analysis, in order to build a functional prototype. As a crucial step in the validation of a rehabilitation device, this prototype must undergo an evaluation of the kinematics and electromyography with a group of patients. Only after the device validation that the

preparation for commercialization should be started. The product development cycle is an iterative process, so many phases can be regressed if the users point out dissatisfaction.

## 5. CONCLUSIONS

The design techniques proved to be fundamental in the early phases of data collection and solution conceptualization, leading to the innovative concept idealization of an upper limb rehabilitation device which resulted in the deposit of an invention model patent BR 1020170023052 (Cavalcanti, *et al.*, 2017). Those techniques served to guide the designing team to create the product concept quickly and directly, taking account the users' needs. Thereunto, the presence of the health professional in the designing team, represented by occupational therapists, was very important. They actively participated in the users' needs interpretation and helped in their extraction into technical characteristics. Moreover, the health professionals were present in all decision-making, emphasizing the users' perspective and explaining the arm movements that the device must assist.

The product decomposition into subsystems was important in the innovative product formulation. As the designing team starts looking for conceptual solutions for simple subfunctions, the possibility to generate different configurations sets grows. To choose the set that best meets the product demand, the conceptual configurations were evaluated by the compliance degree with design parameters, which were related to technical performance, possible risk in the product uses, and economic viability. With the product concept defined, the next steps involve the functional prototype construction and validation with stroke patients' group. This validation should be applied in the kinesiology field, to prove if the device actively assists in rehabilitation activities, as well as in the end-users' approval degree.

## 6. AKNOWLEDGEMENTS

This work was supported by grant #2016-4/442109 of Nacional Council for Scientific and Technological Development (CNPq) and by the funding through doctorate scholarship (CNPq). The authors are grateful to UFTM from the support during therapeutics test.

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