FRUGAL APPROACH FOR THE DESIGN OF A REHABILITATION PHYSICAL SYSTEM

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ABSTRACT

In the rehabilitation process, robotic structures can support the different medical-surgical actions. These recovery process activities often involve repetitive movements that must be performed several times at various amplitudes. Robotic structures for rehabilitation can be driven by three types of active drives, namely electric, pneumatic and hydraulic actuators. Pneumatic systems have become increasingly present in various market segments and are widely used in the industry, mainly due to their ease of maintenance, low cost, safety and applicability in various processes. Currently, the concept of Frugal Innovation is being discussed, which emerges as a way to produce effective and affordable products using fewer resources to reach less-served customers. Frugal Innovation is centered on saving resources, is characterized by simplicity and clarity and aims to reach the low-income market. This article proposes the application of Frugal development methods in the design of a lower limb rehabilitation system. With the application of frugal concepts, pneumatic actuators were chosen. The choice of the pneumatic cylinder is presented from the required pneumatic force. The application of the Frugal Innovation approach in the design of this type of products demonstrates the relevance of applying these methods in efforts to mitigate or reduce the growth of the technological gap between underdeveloped and developed countries.
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Keywords: *Pneumatics systems, Robotic, Rehabilitation process, Frugal Innovation, product development.*

INTRODUCTION

Frugal innovation is a highly relevant innovation concept today [1], [2] and, more broadly, for the development of new products or even enterprises, as well as learning [3]. Nevertheless, according to [4], the concept of frugal innovation has been cited since 2009. Frugal engineering consists of a set of principles and methods used to design and develop low-cost, high-quality products to satisfy the needs of low-income customers in developing markets [5].

World Health Organization (WHO) estimates that over one billion people, nearly 15% of global population, live with at least one kind of disability or 1 in 7 individuals suffers from disability and 2% to 4% have severe difficulties in locomotion [6], [7]. Disability disproportionately affects women, and older and poor people, in particular indigenous individuals and ethnic minorities [7]. Disability is a global health and human rights issue that leads to poor health outcomes, lower educational achievement, and less economic participation and has a higher incidence in low and middle income countries, which include many in Latin America [7].

Cost constraints are also a key issue when considering applications of physical rehabilitation devices in low-income countries [8]. Robotic rehabilitation devices are currently priced in the $75,000 to $350,000 range before any additional hidden costs related to shipping, taxes, maintenance, and installation/training [8]. This is particularly an ominous limitation as 85% of all stroke deaths occur in low- and middle-income countries.

Helping address this research gap, this paper investigates how a constraint-based approach can be applied to the frugal product development for rehabilitation process. Based on the theory of constraints, this work used a structured and iterative approach of constraint-based thinking to define frugal product design requirements for physical rehabilitation.

The approach contains a problem and solution space consisting of the following four iterative steps [9]:

a) the identification of constraints or existing limitations, hindrances behind the status quo that need to be changed;

b) a root-cause analysis to understand the underlying causes for each of the identified constraints;

c) a mapping of each of those causes to specific product characteristics or requirements;

d) development of a minimal viable product or a prototype. To the best of authors' knowledge, this is the first study combining constraints and innovation using an ex-ante approach to develop frugal products.

With the application of frugal concepts, pneumatic actuators were chosen, showing the relevance of applying these methods in efforts to mitigate or reduce the growth of the technological gap between underdeveloped and developed countries.

METODOLOGHY AND USER REQUIREMENTS DEFINITION

Figure 1 provides an overview of the constraints that authors considered critical and influenced the development of frugal product.

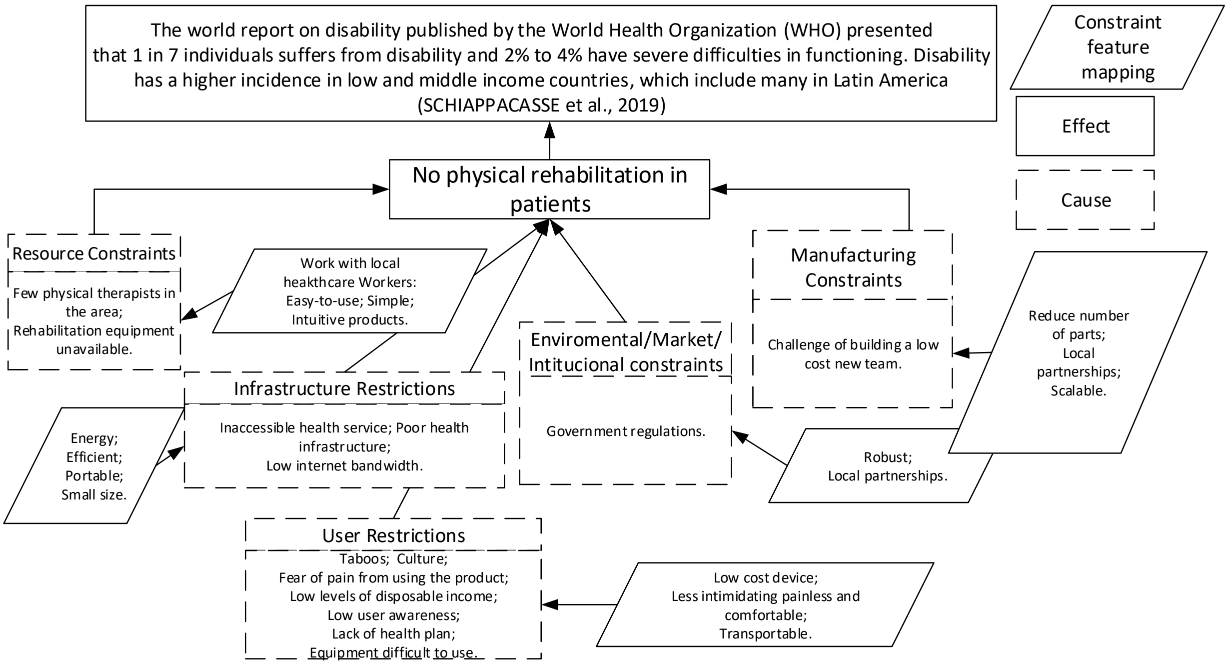

Figure 1 – Mapping of constraints to frugal features for physical rehabilitation products

These constraints are defined based on work that applies constraint-based thinking to frugal developments [9]–[11]. In addition, researches that propose developments of rehabilitation systems in emerging countries are studied for the process of defining the restrictions [8], [12], [13]. In conclusion, the restrictions are defined taking into account the analysis of the restrictions presented in Table 1, in conjunction with the restrictions defined in other similar works and on the analysis of local researches, mainly in Brazil.

According to [9], a number of factors stimulate frugal innovation and can be placed in the categories depicted in Table 1.

Table 1 – Types of constraints

Process Constraints	Product Constraints
Time	Product requirements
Equipment	Customer and market needs
Human resources	Business needs
Money	Intellectual property
Technology	Product legacy
Process legacy	Regulations
Manufacturing capability	Public health
Organizational structure	

RESULTS

A bibliographic review of some physical rehabilitation systems was carried out, then efforts were found such as: [6], [8], [13]–[16]. These efforts are based on proposing mechatronic products to assist the physical rehabilitation process in people; for example, [8] presents a prototype to help recovering mobility in the fingers of the hand; [16] proposed a product for the rehabilitation of upper and lower limbs, that is legs and arms.

These works were evaluated to choose the solution that best represents the listed frugal user requirements (Table 2). The user requirements are listed based on Constraint feature Mapping presents in Figure 1.

Table 2 – Determination of the utility function values of product conceptions

User Requirements	Weight	(JARRETT; MCDAID, 2017)	(GONÇALVES *et al.*, 2020)	(KOÇAK; GEZGIN, 2022)	(GONÇALVES; RODRIGUES, 2019)	(CIOBANU *et al.*, 2018)	(GOERGEN, 2020)
Price	1,6	3	4	4	4	3	4
Transportability	1,5	4	4	4	4	3	4
Complexity	1,4	4	4	4	4	4	4
Supplyability	1,4	3	3	3	3	3	3
Usability	1,3	3	4	4	4	3	5
Robust	1,2	3	3	3	3	3	5
Connectivity	1,2	3	3	3	3	3	3
Aesthetics	1,2	4	4	4	4	4	3
Applicability	1,2	3	3	3	3	3	4
safety of use	1,1	4	4	4	4	4	4
Value of the utility function		44,5	47,4	47,4	47,4	46,1	51,1
Ordering of conceptions		6^{th}	Second	Third	Fourth	5^{th}	First

The weights of each requirement (Table 2) were prioritized through the use of the house of quality (QFD) presented in [17]. The method "Value of the utility function" was used here for conceptions evaluation (Table 2) [17]. As can be seen, the solution that best meets the user requirements according to the triage done in Table 1 is the one presented by [12]. The Figure 2 presents an overview of the concept presented by the authors, where frugal features can be identified, such as:

1. Low price (Manpower costs; component costs; production costs and total cost): [12] is one of the cheapest products in relation to cost/number of rehabilitation functions.
2. Transportability (Weight and modularity or product): [12] is one of the most modularized and transportable products considering its weight and size.
3. Low complexity (number of components, complexity of software and others): Measuring the complexity through to use [18] method, [12] have similar complexity to the other products studied.
4. Supplyability (complexity of finding the components (national suppliers? regional suppliers?, international suppliers?): [12] have national suppliers for its fabrication.

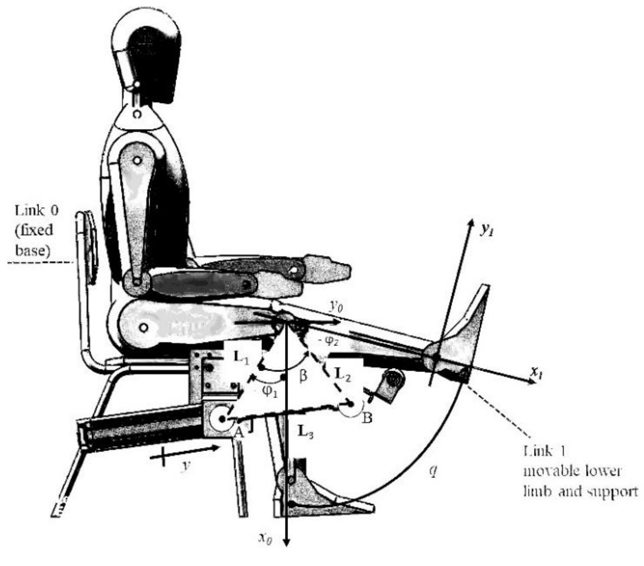

Figure 2. Pneumatically driven robotic bench for upper and lower limb rehabilitation [16]

According to [16], the pneumatic actuators can absorb unwanted forces, because their main energy source is the air, whose characteristic is to be compressive. Moreover, the pneumatic actuators present a high force/weight ratio, implementation with low costs, flexibility for installation and reliability, which characterizes considerable advantages. Consequently, robots that use this technology are getting lighter and show less inertia, resulting in a more secure system.
[16] used the relationship between the actuator length variation ($\boldsymbol{y}$) and the respective joint displacement variation ($\boldsymbol{q}$) given by equation 7; through the use of equation 7, it is possible to arrive at the necessary course parameter in the cylinder y (mm); just enter the necessary angular displacement (q) in the rehabilitation process.

$$y_{(q)} = \sqrt{{L_1}^2 + {L_2}^2 - 2|L_1||L_2|\cos(q - \Delta\varphi) - L_3} \tag{1}$$

Where L_1, L_2, L_3 $and \Delta\varphi$ are construction parameters.

As a proposal, this work intends to use the mathematical models presented by [16] to provide a new concept that reduces costs in the new product since the original idea is considered expensive due to the price of a pneumatic 5/2 valve (>R$400). The Figure 3 presents: a. the original pneumatic drive system of the robot and b. the system proposed as future work.

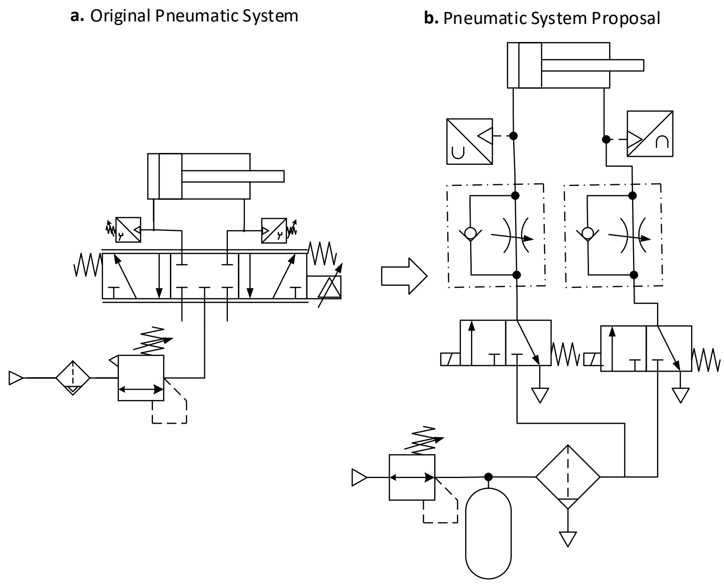

Figure 3. Pneumatic circuit of the robot prototype for limb rehabilitation [19].

The future work has as a goal to build a rehabilitation bench using valves on-off. On-off pneumatic valves are available from R$30. The cylinder sizing methods presented by [20] and [16] will be used.

Other configurations such as the one presented in [33] will be studied to analyze the price of components vs. energy consumption, to conclude which configuration best meets the Frugal and Sustainable approaches.

The assembly of a pneumatic system involves several factors, such as the dimensions of the actuators, the type of cylinder, the precision required in the system and the total cost of the project. When the idea is to carry out a project that can be used on a large scale and that can attract smaller buyers and in emerging countries, it becomes necessary that the main focus is the final cost of the product, and that it can perform the required work without great losses.

This article presents the initial stage of the user requirements definition process for frugal innovations. This work combines the PRODIP reference model and the Constraint-Based thinking method on the way to develop a special methodology for the development of frugal mechatronic products for industry 4.0 and 5.0.

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