

# Development of a device for the reintegration of people with incomplete quadriplegia

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**Abstract:** The product development process (PDP) presents interactive stages to be followed for the release of a product. The study adapts the classic PDP approach to a Project-Based Learning context guide the application for the development of an assistive device that allows people with incomplete quadriplegia to practice paralympic tennis with higher performance and comfort. The study was based on research performed within a nonprofit social assistance Association dealing with disabled people. The research identified that the main barrier faced by players of paralympic tennis is the difficulty to hold, maintain, and transmit power through the racket during the game. Based on this demand, the early stages of PDP were applied in a university PBL and the development of the new solution achieved Technological Readiness Level (TRL) of 2. The final deliverables were CAD model and a conceptual prototype.

**Keywords:** product development process, assistive technology, paralympic tennis, project-based learning.

## 1. Introduction

Wheelchair tennis is an adapted sport modality founded 1976 and is considered one of the most popular sports practiced by wheelchair users. From 1992 to 2016, the International Tennis Federation's Wheelchair Tennis Tour increased from 11 to 160 international events (Alden & Aran, 2016). However, injuries affecting neuromusculoskeletal and movement of the upper limbs of the players during tennis practice are commonly reported, in which 20% occur in the hand, followed by shoulders (15.5%), fingers (11.1%), and arms (10%). According to Caldwell & De Luigi (2018), the incidence rate of injuries in wheelchair tennis is 12.7%, in which 37% are acute injuries and 47% are caused by overuse. Caldwell & De Luigi (2018) states that during the 1992 Paralympics, 75% of wheelchair tennis players acquired at least one injury during training or competition.

Therefore, the racket's grip is decisive to improve performance and avoid injuries during the game, and the way the racket is held influences the racket's front angle, the position in which the ball is in relation to the body, and especially the movements that occur when the impact between the ball and the racket happens (United States Professional Tennis Association, 2018). Many wheelchair tennis athletes have difficulties with the racket tightening

movement (Caldwell & De Luigi, 2018), which can be caused by different reasons, such as poliomyelitis, phocomelia, myopathy, muscular dystrophy or neuropathy (International Tennis Federation, 2017). The mentioned impairments prevent athletes from being able to grasp and completely close the hand to hold the racket.

Although even with the increasing sport's relevance, players still use rudimentary solutions to solve the positioning of the racket's problem, such as tying tapes and bands to bandage their hands. Those improvised and cheap solutions cause high discomfort, excessive sweating, swelling, skin disorders and require a long time for implementation (Carvalho, 2005). Accordingly, research and technological development applied to tennis are focused on commercial sporting materials, such as clothing, balls, and rackets. Consequently, the investments in solving paralympic athlete's problems are considerably low (Carvalho, 2005).

This paper reports the experience for developing a product by undergraduate students based on project-based learning (PLB) perspective during their regular classes, in which the student's team share knowledge and engage their learning throughout the project application of the innovative

product process (Monteiro et al. 2017). The collaborative work promoted in the PBL environment facilitates the acquisition of knowledge around a complex and ill-structured problem through a new product development aiming at achieving Technology Readiness Level (TRL) 2. (Straub, 2015).

Considering this, the problem is to develop an assistive device designed for quadriplegic tennis players who play in Quad modality, classified as wheelchair tennis with a hand problem. Specifically, this project aims to solve the problem of grabbing and transmitting racket's force during the game by practitioners of wheelchair tennis with incomplete quadriplegia in consonance with the product development process theory (Otto & Wood, 2001; Dieter, 2000; Ulrich & Eppinger, 2004).

The objective was to achieve TRL 2 through the development of an assistive technology product project using traditional product development approaches in a PBL environment. TRL 2 involves the transition between the observed and reported basic principles and a technology concept or application formulated. The traditional product development approaches were used to increase knowledge and understanding of the classical PDP within a PBL environment.

This paper is divided into 4 sections. Section 1 presents the research context and the study general objective. Section 2 presents theoretical concepts related to the PBL approach, Paralympic Tennis Quad, PDP, and TRL. Section 3 includes the methods report, section 4 discusses identified results and section 5 discusses the experience, particularities, and possibilities to the future.

## 2. Literature review

### 2.1. Project-based learning approach

The product development stated in this article is based on the PBL approach, an active learning method that became very popular within engineering education, due to its positive impact with realistic outcomes on students learning and engagement (Zancul et al., 2017). It is based on principles of adult learning theory, including motivating the students, encouraging them to set their own learning goals, and giving them a role in decisions that affect their own learning (Wood, 2003).

The PBL supports the development of engineering students by means of practical tasks given by real-life problems or the company's requirements. The PBL approaches provoke students to investigate a real-life problem that could be sorted out by means of a product or to bring a requirement of any company, with the regard to promote knowledge expansion in product development for the students rather than solve a company need.

The proposed teaching approach demonstrated efficiently to undertake two of the challenges faced by engineering undergraduate education for product development, the need to foster interprofessional educations and collaborative work, and to provide a complete interdisciplinary view of the information flow that enables ideas to be developed into real products (Zancul et al., 2017). The real constraints placed on functionalities, materials, manufacturing processes, or specific markets, provide new challenges for students, more than an internal project. Activities involve active learning from the company's experts by organizing team meetings that include staff from manufacturing and marketing in cases where the tasks are guided by the company's requirements (Shekar, 2007).

### 2.2. Paralympic tennis quad

The International Tennis Federation is the officially recognized entity with the authority to control official tennis rules worldwide. It regulates the official rules of tennis for people who do not have disabilities and for athletes who play tennis in a wheelchair, Quad, or open division within the sport in order to reduce the effect of the disability on sports performance (International Tennis Federation, 2017).

According to the International Tennis Federation (2017), athletes who wish to compete in the Quad category must meet at least one of the following requirements: (1) Reduced motor function required to perform an overloaded service; (2) Reduced motor function required to perform forehand or backhand; (3) Reduced motor function required to operate a manual wheelchair, (4) Inability to hold the racket, requiring the need to cover and/or use a support device to play.

According to Bardales (2013), the importance of gathering information from existing technologies and similar products consists of generating a consistent base of pieces of evidence about the functions of similar products and products that meet the needs of customers. The available evidence directly influences the cost estimate of the alternatives of the product under development and can include everything from product characteristics to material type properties and specifications.

Furthermore, the solutions currently applied involve rudimentary technological robustness, choosing materials such as gloves, ribbons, bows, and glues to tie the hand to the tennis racket. This lacking technological innovation is also a strong warning paving the way to develop new products, which are capable of enabling and improving the experience of tennis players, professional or not, in the Paralympic modality called "Quad" (Carvalho, 2005).

### 2.3. Product development process

The product development process consists of a set of activities that, based on market needs, technological restrictions, and strategies of the company, seek to reach the

project specifications of a product and its production process (Rozenfeld et al., 2006). Moreover, it is a competitive strategy led by-products and environmental sustainability, which begins with the perception of a market opportunity and ends with the production, sale, and delivery of a product (Ulrich & Eppinger, 2004).

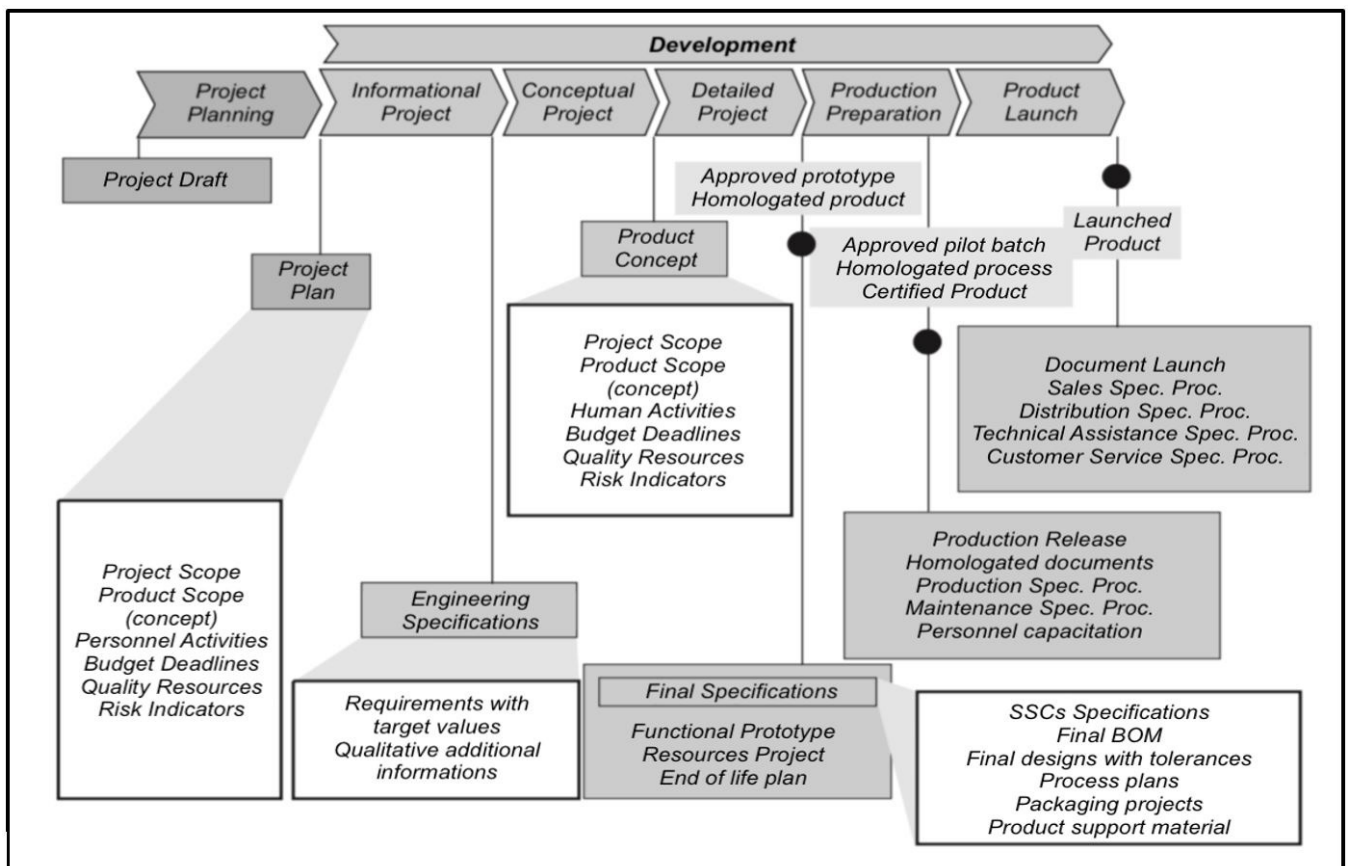
Conversely, the product development process has several problems in the progress of theory and concepts (Shaw, 1995). Many problems in the production area derive from the lack of theoretical studies based on a systematic method (Conforto et al., 2011). Besides, Hart & Moore (1997) highlights the relevance of investigating and understanding the knowledge broadly before starting research. Therefore, the problem definition is the starting point for the scientific review during the product development process (Conforto et al., 2011). The main phases of the product development process and the expected results of each step are illustrated in Figure 1.

According to Bardales (2013), the product development process starts with an idea or demand from the internal customer, and later the sales team starts the prospecting and survey phase with external customers and possible interested parties. Market research integrates the consumer, customer, and community with professionals through information.

It involves the processes of collecting information from different data sources, that can be divided into two main sources: primary and secondary (Rozenfeld et al., 2006).

Primary sources provide data directly available from the user, considering the project needs. Secondary sources make available information for other purposes that, although have not been acquired for the primary needs of the project, are useful. Qualitative research uses methods capable of analyzing abstract information, such as consumer concepts, for example, materializing user's perceptions. Direct observation and content analysis from transcribed speeches are types of qualitative research, in which the researchers have access to consumer's opinions directly when they are exposed by the first time to the product or its primary idea (Rozenfeld et al., 2006; Madzik et al., 2019).

After defining the problem, the following step is to define the product life cycle, that provides a graphical description of the product's stages and depends on the type of project, production scale, operating characteristics, among others. In order to define the customer requirements, analysis, and categorization of the customer needs considering each lifecycle stage are necessary, through classifications, ordering, and grouping techniques. Customers can express themselves in terms of product failures or expectations and



**Figure 1.** Product Development Process phases and deliverables. Sources: Rozenfeld et al. (2006).

this gathering information can be represented graphically through the Kano Diagram, which considers customer satisfaction versus product performance (Kano et al., 1984; Madzik et al., 2019).

Subsequently, the product specifications are derived from the customer's requirements (Hauser & Clausing, 1988). The informational project aims to develop the product's target specifications, through the information collected in the planning phase (Back et al., 2008).

The specifications guide design solutions and serve as a basis for assembling the evaluation and decision-making criteria used in the following PDP stages. In order to obtain accurate communication during the project, the customer requirements are translated into technical engineering language because customer needs tend to express customer's wishes in a subjective way. The conversion of product requirements into product specifications defines measurable parameters, associated with product characteristics (Akao, 1990; Kwong et al., 2007; Franceschine & Maisone, 2015; Madzik et al., 2019).

According to Back et al. (2008) and Rozenfeld et al. (2006), unlike the informational project phase that deals with the acquisition and transformation of information, the conceptual project consists of the search, creation, representation, and selection of solutions to the problem, aiming at obtaining the product design. The conceptual design phase ideally follows a linear process but typically is realized through a highly iterative one. The design problem is elucidated, and function decomposition follows. Solutions for each sub-function are identified and combined to create a potential integrated conceptual design (Clausing, 1994; Ullmann, 1997; Ulrich & Eppinger, 2004).

The morphological chart represents a methodology for organizing alternative solutions for each function of a product and combining them to generate solutions variants that potentially satisfy the product functional analyses. The outcome for the morphological chart is based on numerous possible concepts, derived from the combination of Solution Principles for each function identified. (Pahl et al., 2007, Mansor et al., 2014). Although, the concept generation needs

to be guided by experienced designers to identify conflicting Solution Principles (Yang & Basen, 2008; Liverani, et al., 2019).

## 2.4 Technology Readiness Level

The TRL has a long history at NASA and the American Department of Defence when designing and testing new technologies (Mankins, 1995). The method was created to assess the maturity level of new technologies developed at the agencies to predict the time and readiness to application in real case scenarios. The advent of these metrics provided a valuable tool for communication between the research and development (R&D) departments and those involved in both ongoing and proposed projects (Hicks et al. 2009). The TRL is based on nine levels of development, with specific descriptions of each level to assess the development of projects and technologies. The nine levels are summarized in Table 1.

Although the TRL approach determines the maturity of technologies. The product development process is not linear process. The TRL system recognize the time of and degree of technical risk of technology development. Product development and advancement depend on a multitude of factors, including new and emerging technologies, as technological leadership is often a key product differentiator (Hicks et al., 2009, Salerno et al., 2015).

In order to prevent the limitations for the TRL in product development, in this article, the concept for TRL level 2, the desirable level for the proposed PBL exercise, will be the development of a concept, regarding the PDP tools, prior the analytical and laboratory experimentation for proof of concept.

## 3. Methodology

The University of Brasilia (UnB)'s Industrial Engineering undergraduate program presents an innovative curriculum, which is based on the Project Based Learning methodology (PBL). The program has been designed with a length of 12 semesters. It first began in the second half of 2009, and graduated its first group of engineers in the second semester

**Table 1.** Technology Readiness Level definition based on nine levels of development (Hicks et al., 2009).

TRL	Definition
1	Principal research into the core properties of a technology.
2	'Invention' of a concept or application for the technology. Shift from principle to applied research.
3	Initial 'proof of concept' of critical functionality through active R&D (Analytical and laboratory studies in appropriate context to validate previous analytical predictions).
4	Low-fidelity validation in laboratory environment. Technological advancement now focussed on meeting project requirements.
5	Validation of basic technological elements in a relevant environment. Test 'set-up' to be of higher fidelity than at TRL 4.
6	High fidelity 'alpha' prototype demonstrated in a relevant environment.
7	'Beta' prototype demonstrated in an operational environment.
8	Completed component, sub-system or system qualified to relevant project requirements and/or regulatory standards.
9	Certified component, sub-system or system proven to meet all project requirements through 'real world' operation.

of 2014. The program features eight courses labeled Production Systems Projects (PSP), all of which apply the PBL approach, and are held from the 3rd to the 5th year of the program (Monteiro et al., 2017).

This paper reports the experience for developing a product by undergraduate students based on project-based learning (PLB) perspective during their regular classes, in which the student's team share knowledge and engage their learning throughout the project.

According University of Brasilia (UnB)'s Industrial Engineering undergraduate program in course of Production Systems Design 6 (PSP6) are knowledge explored about the Product Development Process. This course is an interdisciplinary with greater technical complexity than compared to others of the same nature in curriculum of program.

In the first class, the problems are presented by external agents and then teams are formed. This paper presents the evolution of a team that worked with development of a device for reintegration of people with incomplete quadriplegia.

The external agent was the *Centro de Treinamento Educação Física Especial* (CEFETE) which is a non-profit organization that provides free services to people with some type of physical disability. A tennis instructor, a physiotherapist, five athletes and two teachers were involved in the design process.

The process to develop of the new device based on the PDPnet, focusing on 4 main steps: (1) Data collection on customer needs; (2) Conversion of customers' requirements into product specifications; (3) Morphological chart and solution principles and (4) Design of the first prototype.

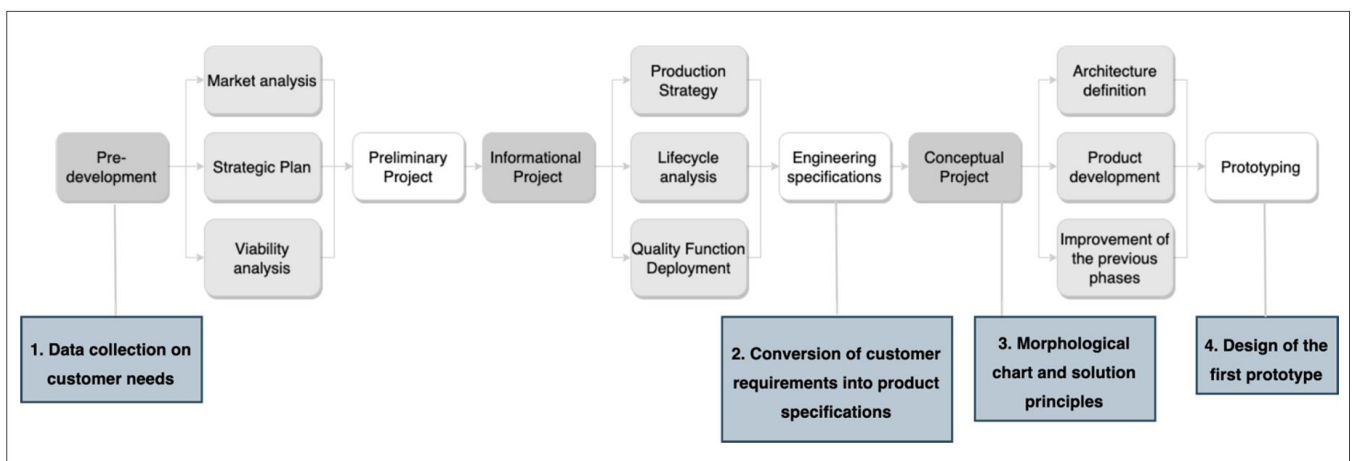
The study object is the use of the PDPnet process reference model developed by Rozenfeld et al. (2006) for the project of a product that allows reintegration of people with incomplete quadriplegia in a specific sport, using data

to translate the user needs to user requirements, product requirements, solution principles, and a prototype aiming to achieve TRL 2. The overall step by step of the project structure of the product development is represented in Figure 2. The steps 1 to 4 were described in this article.

As listed, the first step was the data collection on customer needs. At this stage, primary and secondary sources, as well as direct observations were applied to collect human perception. With reliable techniques of data collection, we classified user needs translating into customer requirements, concerning the lifecycle phases. The second step was to convert customer requirements into product specifications. An evaluation of customer satisfaction and product performance through a Kano Diagram allowed us to highlight the customer requirement's prioritization. This stage was crucial to define the first definition of critical product parameters.

In order to establish valuable product specifications, a functional analysis was performed in the third step. This is based on the main function the product needs to execute and the logical steps to achieve it. Therefore, the logical steps are translated into basic functions, following a hierarchical relationship each time a function needs to be decomposed in two or more. Afterward, we applied the Morphological chart to generate alternative solutions and three concepts were generated using combinations for the solution principles proposed at the Morphological chart.

The evaluation of the best concept was performed according to a compliance degree with the product requirements. With the definition of a concept, a prototype was proposed in the fourth step. In order to design the prototype, we created CAD (Computer-Aided Design) models. The concept was adapted to make possible the use of shelf products, such as locking systems and wearables. The concept was manufactured using FDM printers and the final assembly was performed by the university team.



**Figure 2.** Project structure adopted for this study. Sources: the authors (2019)

## 4. Results

### 4.1. Data collection on customer needs (user-centered approach)

To identify the customer needs, three main techniques were used for data collection: (a) survey of primary sources, which consists of conducting interviews with those responsible for Training Center and Paralympic athletes, (b) survey of secondary sources, which includes scientific researches and methods to assist in the study, and (c) direct observation, which consists of technical visits to the site to assist in the product project.

The main objective of the survey of primary sources was to specifically identify the customers and list the involved problems of tennis players with disabilities. A questionnaire was designed, considering the player's problems and complications, difficulties, and undesirable outcomes faced during the game. A survey through questionnaire-based interviews with members of the Training Center and Paralympic athletes was followed by a documental analysis and reports from the training programs and games. We identified that the players continuously use ribbons to grab the racket and this causes allergies, circulation problems, discomfort during the game, loss of time while attaching the hand, and loss of money to buy disposable ribbons. The use of ribbons caused injuries in many players, affecting the wrist, shoulder, and elbow movements and amplifying several diseases or physical disabilities such as multiple and lateral sclerosis, polio, atrophy, dystrophy, brachial plexus injury, peripheral nerve injury, among others.

The general purpose of the survey of secondary sources was to measure how the target customers feel towards a new product that helps to grab the tennis racket. A market research questionnaire was designed and a survey was conducted with Brazilian Quad players. In 2018, 313 players were classified in the Olympic Quad category. Of these, the country with the most participants in Japan with 18%, followed by the United States with 15%. Moreover, 274 of the 313 players who reported their year of birth, 57% were born between the 60s and 70s. Therefore, the majority of the public practicing this sport is between 39 and 58 years old. Another factor found was that 90% of athletes are male. Brazil had a total of 8 players registered in 2018. In 2015, 257 players were classified in this category, with a total of 4 Brazilian players.

We verified that 80% of the Brazilian players have reduced strength in their hands or C6/C7 spinal cord injuries or difficulty holding the racket throughout the game, but they believe that the tennis practice helps to deal with the disability. Besides, the disability affects the racket backhand movement, maintaining the racket at impact with the ball, positioning the racket, making the movement with

both hands, and holding the racket. Moreover, 75% of the Brazilian players use adaptations such as Durex, tapes, ribbons, or adhesives during the game or training. The direct observations consisted of technical visits to the site, observation of videos in conventional tournament games, and Paralympic tennis.

The collected data was divided into bibliographic, documentary, and statistical data and classified as macro necessities within each stage of the product life cycle. An analysis of the product lifecycle at this stage was important to maximize the value of the customer's needs (Stark, 2015; Zhang et al., 2017). The stakeholder analysis and activities deployment within each lifecycle main activity provided a view of the main approach: assemble to order, in which final products are assembled only after customer orders are made. Despite the commonly known problem with component commonality, the degree of modularity, postponement and substitution were considerably high.

The macro necessities were grouped into the attribute's operation, ergonomics, aesthetics, economical, normalization, and modular. The categorized macro necessities were subdivided into primary necessities, identified its scenarios, and mapped into customer requirements. Table 2 shows the breakdown of macro necessities identified with the collected data into customer requirements. The necessities correspond to one, two, or three customer requirements and the scenario's correlation was fundamental to define and categorize main terms identified on customer needs. These requirements were analyzed regarding its necessities and impact through a Kano diagram.

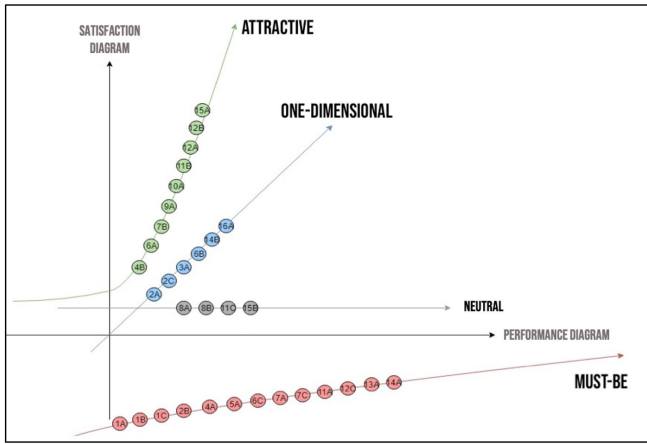
### 4.2. Conversion of customer requirements into product specifications

One of the main purposes of the Kano diagram (Figure 3) was to connect the requirements fulfilled with customer satisfaction and identify three ultimate influences: must-be, one-dimensional, and attractive. The Kano diagram showed that requirements number 4B, 6A, 7B, 9A, 10A, 11B, 12A, 12B, and 15A leads to greater satisfaction, whereas it is not expected to be in the product. The fulfillment of attributes number 2A, 2C, 3A, 6B, 14B, and 16A helps to increase satisfaction and vice-versa. Absence of attributes number 1A, 1B, 1C, 2B, 4A, 5A, 6C, 7A, 7C, 11A, 12C, 13A, and 14A produces absolute dissatisfaction and its presence does not increase satisfaction. Besides, to this classification, must-be attributes should be kept, one-dimensional and attractive attributes should be added, and neutral attributes should be avoided (Harjith & Naduthodi, 2017; Sharif Ullah & Tamaki, 2011).

The Kano diagram showed the need to find new requirements that impact customers, but these requirements are generally still in the form of needs, without being

**Table 2.** Breakdown of the macro necessities into customer requirements.

Macro Necessities	Primary Necessities	Scenario	Customer Requirements (A)	Customer Requirements (B)	Customer requirements (C)
Needs of use	1. Be functional	Product solves the customer problem	1.A Secure locking to players hand	1.B Allows transmission of power to the racket	1.C Secure locking to the racket
	2. Don't hurt	Safe product and no health risk to the athlete	2.A Lightweight	2.B Allows free blood circulation	2.C Possess comfortable materials
	3. Easy to prepare the use	Low time to prepare the use	3.A Easy to assemble and disassemble		
	4. Possibility to store the product after use	Product can be stored without difficulties	4.A Easy to clean	4.B Be reusable	
Respect to the customer protection laws	5. Adherence to the codes, statutes and defense bodies		5.A Contain recommendations and side effects for product use		
Accordance with physiological needs of different users	6. Contain components in compliance with different profiles of special needs	Different injuries and problems may be served by the same product	6.A Be adaptable	6.B Easy to use	6.C Have a format that does not bring risks to user health
Accordance with basic physiology of the user	7. Consider folds anatomy, hand bows and three points of hand, fist and forearm pressure	Ergonomic product developed for human use	7.A Be adjustable to user needs	7.B Contain only curved and rounded corners	7.C Free of sharp corners
Effective storage	8. Don't easily damage	Easy and secure product to be stored in large scale	8.A Support humidity and temperature use conditions	8.B Have drop resistance packaging	
Accessible maintenance	9. Cheap maintenance	Cheap and accessible product	9.A Easy to disassemble components		
	10. User security in case of product defect	Secure product with maintenance support	10.A Contain after sales information		
Disposal	11. Easy disposal and high durability	Durable product with easy disposal	11.A Last for expected life time	11.B Be adaptable to other uses	11.C Contain information for sustainable discard
Aesthetic	12. Pleasant color but not flashy	Athletes don't worry too much with the product aesthetic	12.A Have a nice visual aspect	12.B Contain color variety	12.C Small package size
Accordance with the quality standard	13. Guarantee full functioning in compliance with quality standards	Product has compliance with technical specifications and its purpose	13.A Size restrictions according to hand/ arm devices		
Assembly	14. Simple assembly	Product contain a manual with detailed information about how to assemble components	14.A Secure locking of components to main module	14.B Be intuitive and didactic for components assemble	
Reliable transportation	15. Easy to transport	Product easy to carry and transport	15.A Easy to carry package	15.B Contain only one packaging volume	
	16. Secure quality and integrity of the product during transport	Certified transport with low incidence of problems	16.A Be impact and risks free		



**Figure 3.** Kano Diagram. Source: The authors (2019)

associated with measurable characteristics. To obtain accurate communication during the development, the technical language of engineering must be in accordance with the information that characterizes the product. This stage of conversion of customer requirements into product specification, which can be observed in Table 3, was the first physical decision about the product. Most of the customer requirements were translated into only one product requirement (in Table 3) with the exception of the comfort of the device, which can be seen as the balance between tensile strength and elasticity module of the materials used.

Most of the main concerns of the customers were related with the time and ease to assemble and disassemble the device, given that one of the most used solutions (taping

**Table 3.** Customer requirements and converted product specifications.

ID	Customer Requirements	Product Specifications (A)	Product Specifications (B)
1.A	Secure locking to players hand	Locking force [N] (+)	
1.B	Allows transmission of power to the racket	Tensile Strength [MPa] (+)	
1.C	Secure locking to racket	Locking force [N] (+)	
2.A	Lightweight	Weight [Kg] (-)	
2.B	Allows free blood circulation	Hand compression [Pa] -	
2.C	Possess comfortable materials	Tensile Strength [MPa] (+)	Modulus of Elasticity [MPa] (-)
3.A	Easy to assemble and disassemble	Time to couple components together (s) (-)	
4.A	Easy to clean	Washing time (s) (-)	
4.B	Be reusable	Lifetime (cycles)	
5.A	Contain recommendations and side effects for product use	Recommendation quantity/ Contraindications (n) (+/-)	
6.A	Be adaptable	Number of possible global functions (n) (+)	
6.B	Easy to use	Time to prepare (t) (-)	
6.C	Have a format that does not bring risks to user health	Length of material (cm) (-)	
7.A	Be adjustable to user needs	Number of adjustments (n) (+)	
7.B	Contain only curved and rounded corners	% of rounded corners. (%) (-)	
7.C	Free of sharp corners	Quantity of sharp corners (n) (-)	
8.A	Support humidity and temperature use conditions	Resistance to corrosion (% of stainless components) (+)	
8.B	Have drop resistance packaging	Tenacity (J) (+)	
9.A	Easy to disassemble components	Time to disassemble (t) (-)	
10.A	Contain after sales information	Quantity of maintenance recommendations (n) (+/-)	
11.A	Last for expected life time	Life time (T) (+)	
11.B	Be adaptable to other uses	Number of possible global functions (n) (+)	
11.C	Contain information for sustainable discard	Quantity of recycling recommendations (n) (+)	
12.A	Have a nice visual aspect	Percentage of visual aesthetics acception((Number of acception/total)*100)(+)	
12.B	Contain color variety	Number of possible colors (n) (-)	
12.C	Small package size	Volume of device (cm <sup>3</sup> ) (-)	
13.A	Size restrictions according to hand/arm devices	Diameter (cm) (+/-)	
14.A	Secure locking of components to main module	Components precision (mm) (-)	
14.B	Be intuitive and didactic for components assemble	Time to assemble(t) (-)	
15.A	Easy to carry package	Quantity of components that facilitate transportation (n) (+/-)	
15.B	Contain only one packaging volume	Number of packages in each delivery (n) (-)	
16.A	Be impact and risks free	Materials Elasticity (E(Youngs Module) (+/-)	



the hand to the racket) was reported as was reported as time demanding and if it was done in a wrong way, would be time-consuming to reassemble. This generated some product specifications that were measured with time such as time to prepare, couple components, assemble, and disassemble. Another important concern of the users was the solution should be comfortable, which can hurt the player's hands in prolonged use. This calls to the importance of the material that will be used for the device. A balance between strength, so that the players have a firm grip on the racket and elasticity so that the material isn't too hard on the hand and arms are observed on the product specifications.

### 4.3 Morphological chart and solution principles

Based on the scenario of use an analysis of functionalities was executed. This analysis helps to understand the functions that the product needs to perform and to start developing solution principles (SP) for each task that the product needs to achieve.

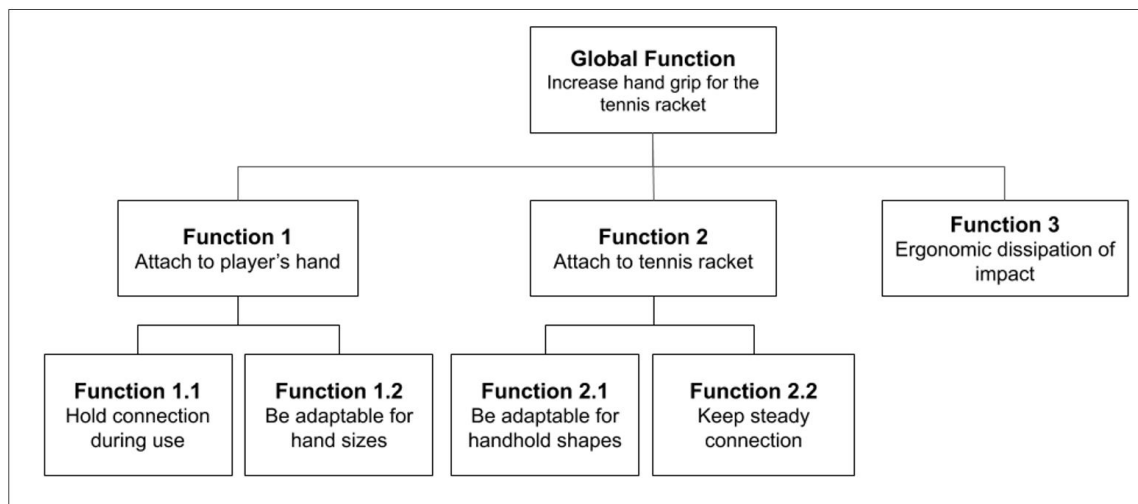
The functional analysis developed by the university team designated a main function for the product, to increase the handgrip for a tennis racket. In order to perform its global function, seven basic functions

were mapped, as presented in the functional analyses illustrated in Figure 4. Subsequently, SP's were proposed for each basic function, developing a morphological chart, presented in Table 4.

The morphological chart presents structured paths to define product architecture. To achieve a final design for the product three concepts were chosen from the options denoted in the morphological chart. The three concepts are illustrated in Figure 5. To evaluate the concepts, a matrix correlating each concept to the product requirements was developed. The best concept was selected through a sum of scores for each requirement compliance degree. As a rule, to denote each score, concept 1 was selected as a pattern and all his scores were considered 0, for the remaining concepts a score of +1 or -1 was derived through comparison. The final scores were 0 for concept 1, +1 for concept 2, and -1 for the third concept. Consequently, the selected concept was concept 2.

### 4.4 Design of the first prototype

In order to obtain a better understanding of the chosen concept and its respective functions, a rapid prototype was proposed. The module designed to hold the racket was



**Figure 4.** Functional Analyses including global function and seven basic functions. Source: The authors (2019)

**Table 4.** Morphological Chart based on seven basic functions.

ID	Function	Solution principle 1	Solution principle 2	Solution principle 3	Solution principle 4
1	Attach to player's hand	Tape	Glove	Rope/wrap	Arm connection
2	Attach to tennis racket	Lock for fingers positions	Magnetic connection	Squeezing feature	Snap fit
3	Ergonomic dissipation of impact	Ergonomic design	Absorptive material	Uncoupled modules	
1.1	Hold connection during use	Locking Tissue	Glue	Tape	Mechanical lock
1.2	Be adaptable for hand sizes	Flexible characteristic	Locking Tissue	Adjustable wraps	Interchangeable components
2.1	Be adaptable for handhold shapes	Flexible characteristic	Interchangeable components	Adjustable wraps	
2.2	Keep steady connection	Locking Tissue	Glue	Tape	Mechanical lock

modeled using CAD software, presented in Figure 6. The numbered features represent solutions for adaptability (1), easy and fast locking and releasing (2), comfort (3, 5), and reduction of stress over hands and wrist (4). To manufacture the module designated to hold the racket the Fused Filament Fabrication (FFF) process was selected. The FFF is a consolidated manufacturing process for fast prototyping,

for that reason, it was selected to fabricate it. To simulate the hand bandage a hand-split was adapted to the product, using a locking tissue to wrap the component and secure locking during tests and analyses. To perform the locking feature for the racket to the structure, a fast locking system for bicycle seats was adapted to the prototype. The prototype is present in Figure 6.

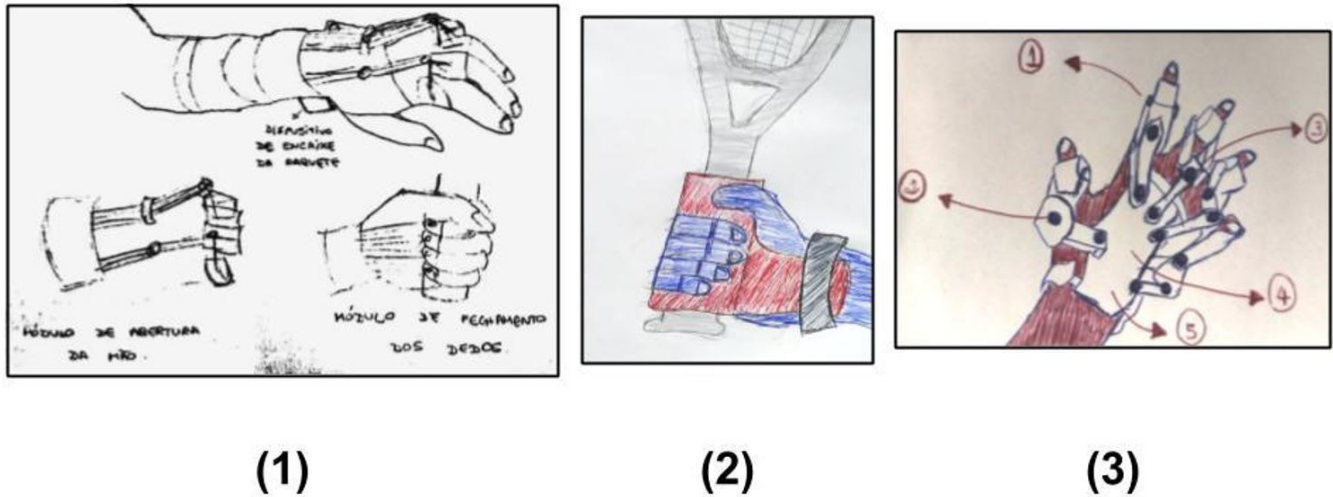


Figure 5. Proposed concepts. Source: The authors (2019).

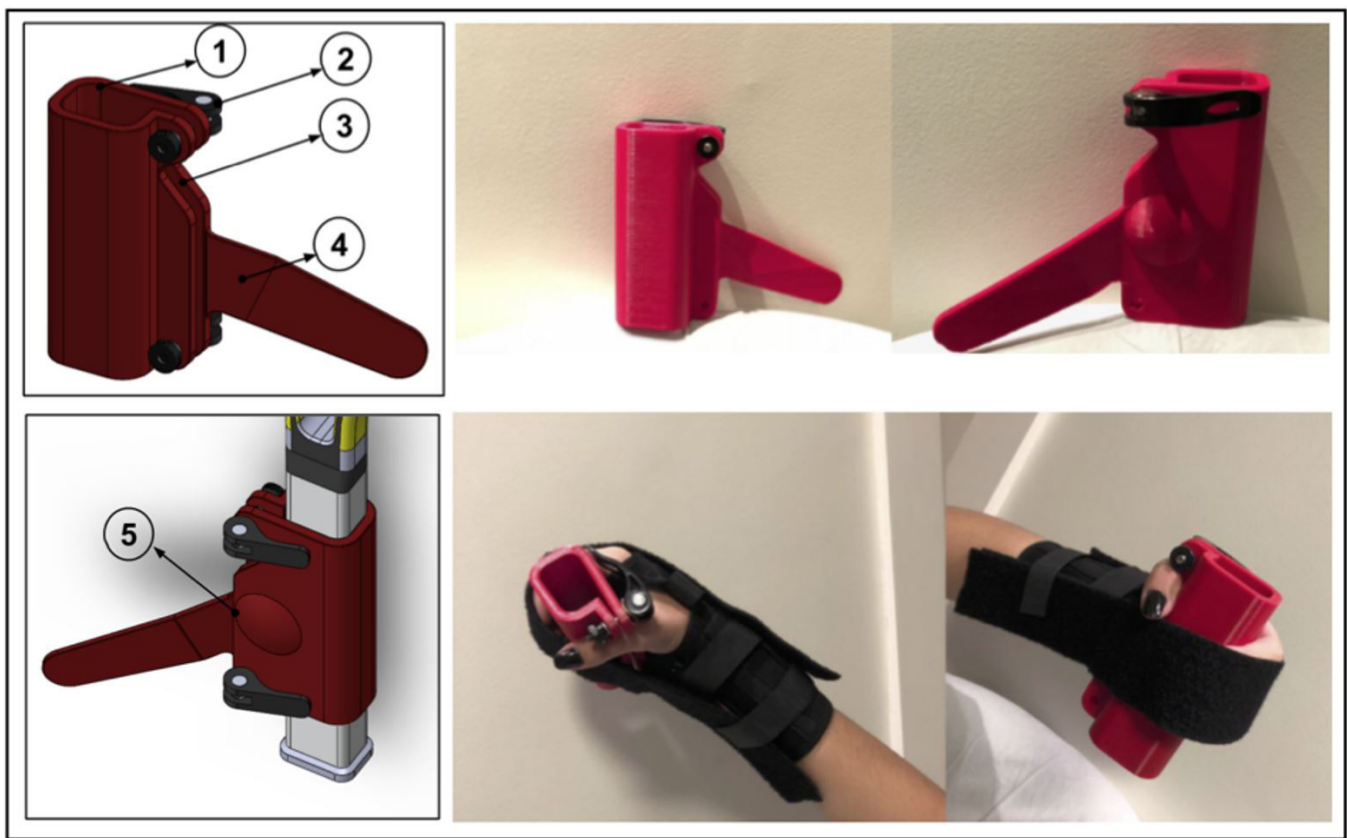


Figure 6. CAD modelling for selected concept and first product prototype. Source: The authors (2019).

The evaluation of the manufactured prototype was executed only by user experience, this evaluation was performed by the development team and members of the Training Center. The analyses depended on the experience for comfort, the sensation of grip, and impact evaluation. The decomposition of loads with the forearm presented a consistent reduction of the stress over the wrist. The attachment to the racket and the hand were possible to be made by the user. The features to improve the sensation of grappling and the rounded corners made the use comfortable and with a safe feeling.

## 5. Conclusion

Regarding the PBL deliverables, the desired TRL was achieved with the concept definition to be proved. As stated by Hicks et al. (2009), a TRL 2 level project must present an 'Invention' of a concept or application for the technology. The prototype validation obtained through interviews with members of the Training Center demonstrates appropriate technical basic characteristics, ergonomic quality, and conformity with the theoretical framework used in its construction. The prototype presented a modular design and portability, promoting safety and functional accessibility for quadriplegic tennis practitioners.

Therefore, the study identified that despite the restricted market, the solutions currently applied are rudimentary and compromises the participation, motivation, and sporting athletes' evolution. It was observed that the prototype, besides helping racket support, potentially promotes upper limb protection, one of the main injury causes also in non-disabled athletes. Besides, it was identified that users' anthropometric characteristics, level of quadriplegia, and specific sport regiments must be considered for the product project. Interviews indicated explicit and implicit player's needs and the questionnaires applied proved to be effective in identifying musculoskeletal obstacles related to pain.

The product development achieved the technology readiness level (TRL) 2 in the inventive step and has a high level of objectivity and reproducibility, allowing the concept use in future works. Considering this context, it can be analyzed that the research presented technical information and practical configurations in the product project, enabling the reintegration of people with incomplete quadriplegia in Quad tennis modality. To continue the research the next steps are related to analytical and laboratory studies, to confirm if the concept is viable and ready to proceed further throughout the development process.

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