

From Modern Push-Button Hospital-beds to 20th Century Mechatronic Beds: A Review

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Abstract. The aim of this work is to present the different aspects of modern high complexity electric beds of the period 1940 until 2000 exclusively. The chronology of the product has been strictly divided into three big stages: electric and semi-electric beds (until the 90's), mechatronic beds (90's until 2000) and, mechatronic intelligent beds of the last 15 years. The latter are not considered in this work due to the extension for its analysis. The justification for classifying the product is presented under the concepts of medical, assistive and mobility devices. Relevant aspects of common immobility problems of the different types of patients for which the beds are mainly addressed are shown in detail. The basic functioning of the patient's movement generator and the implementation of actuators, together with IT programs, specific accessories and connectivity means and network-communication shown in this work, were those that gave origin to current mechatronic beds. We present the historical evolution of high complexity electric beds by illustrating cases extracted from a meticulous time line, based on patents, inventions and publications in newspapers and magazines of the world. The criteria adopted to evaluate the innovation were: characteristics of controls; accessories (mattresses, lighting, siderails, etc.), aesthetic and morphologic properties and outstanding functionalities.

1. Introduction

The design of high complexity beds constitutes a specific field of research in the area of medical products, presently in expansion and development. Despite the historical existence of numerous manifestations of support surfaces for unwell and bedridden patients, a more defined point of origin for these products could be assigned to beds with adjustable siderails, which appeared in England between 1815 and 1825 [1]. Andrew Wuest and Son, registered, in 1874, a patent for a type of mattress frame with a hinged head that could be elevated [2]. Later, a series of efforts converged, originating the so-called push-button hospital beds in the 40s, decade from which the present work commences. At present, there is a whole chronology of products that start with the modern electric beds, in a strict sense, further moves to semi-electric models (that combine adjustments assisted by actuators with manual adjustment sections, still existing as alternatives of minor complexity) to finally arrive to the so called mechatronic beds, which incorporate software into specific motion programs, and display more advanced integrations between mechanics, electronics and computer science in its

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core. Turning into the 21st century, the intelligent mechatronic bed appears, which will be studied in a separate work. This bed includes a higher level of services and functions, including multiple actuators for surface movement, specific automation, monitoring and status data registering functions, as well as additional communication means between the patient and personnel of care.

This work presents: a) A putting into context of the product and its classification as such, b) A brief review of the immobility problem, common to most pathologies and patients (pressure ulcers) that give origin to the existence of these products; c) A basic scheme for the understanding of the required movements of the bed, as well as a model that provides specific functions of mobilization and control in addition to the basic ones (illustrated in a 1992 patent of the University of Buenos Aires); and, d) A diachronic study, starting from the early electric beds up to the mechatronic beds of late 20th century. The cases shown in this work were extracted from a time line that include the date of registry of patents, inventions and publications in journals and magazines of the world.

The adopted criteria to evaluate the innovative aspects of each product were: a) Control characteristics; b) Accessories (active or passive mattresses, lighting, siderail support, etc.); c) Aesthetic and morphologic properties; and, d) Outstanding functionalities.

2. Development of the study

2.1. High complexity electric beds: medical, assistive and mobility devices.

According to the definition of the US Federal Food, Drugs and Cosmetic Act a medical device is:

"an instrument, apparatus, implement, machine, contrivance, implant or other similar, including a component part, or accessory which is (...) intended for use in the diagnosis of disease or other conditions, or in the cure, mitigation, treatment, or prevention of disease (...) or intended to affect the structure or any function of the body (...) and which is not dependent upon being metabolized for the achievement of any of its primary intended purposes." [3]

The World Health Organization (WHO) extends this criterion explicitly, incorporating this group into the diagnosis, treatment and healing of wound solutions, vital support systems, disinfection equipment and software developed for these purposes, among other definitions [4]. Therefore, high complexity electric beds are a specific type of medical device included in one of the 10,000 [4] categories covered by the mentioned definition. In recent years, the devices of high resolution image generators, tomography, magnetic resonance, and more recently, the definitive incorporation of the robotics in all of these, are examples of innovation in medical complex products. This trend has deepened the merging of medical devices with isolated IT and network systems [4], opening the path to a new age of products integrating electronics and communications. Thus, the evolution of the electric beds into intelligent mechatronics is paradigmatic.

In this context, it's possible to go in depth into medical devices up to the so called *assistive devices*. These are outlined in search of supporting or improving functions and to minimize the operational difficulties of its users. A definition for this type of devices is:

Any product (including devices, equipment, instruments, technology and software), produced specially or available in general, used by or for persons with disabilities, for their participation, protection, support, training, measuring or substitution of functions, structures or activities, or to avoid limitations or restrictions for their participation in activities" [4]

Thus, high complexity electric beds constitute devices of excellent assistance, since they are particularly conceived to mitigate and to anticipate the secondary health conditions associated to immobility, both for patients transitorily immobilized as well as for patients suffering chronic conditions of variable severity.

An important subgroup among the *assistive devices* to which high complexity electrical beds belong to is the subgroup of *mobility devices*. These are products or technologies that allow disabled

persons to displace, mobilize, support and change their corporal positions, constituting “a prerequisite to reach equivalent opportunities, exercise their rights (...) and live in dignity” [5]. These products can improve health of users reducing the risk of falls, injuries and other limitations that can result in complications and premature mortality. Due to the sensibility of the subject, the WHO proposed and assigned a number of valuable design principles for their provision and success, such as *acceptability, accessibility, adaptability, availability, low cost and quality* [5].

2.2. From the immobility of the patient to the mobility of electric beds

High complexity electric beds respond with movements, to the lack of mobility of patients. But these movements are the product of a specific biomechanics, which is a particular field of knowledge in itself, tied to the evolution and improvement of the design of these products. The potential complications resulting from immobility are multiple: besides the changes in the mental condition of patients (depression) and pressure or of decubitus ulcers, muscular atrophy, bone demineralization, pneumonia, gas exchange dysfunction, thrombosis in deep veins, and edemas, are found among other serious conditions.

The duty of positioning a patient by regular intervals of time, achieving a better distribution of pressure, follows well-known protocols based on the practice and experience of the personnel of infirmary. This is an intensive task that generally falls upon the auxiliary personnel, assistants or patient's relatives. This additional dedication, necessary to the treatment and prevention of pressure ulcers, has a drastic impact on the associated costs of the medical system at multiple levels [6], being a serious concern for budget allocations of health organizations, at both national and international level.

2.2.1. Pressure ulcers

Pressure ulcers are a typical example of complications associated to lack of mobility and sensibility. Since 1932, it is considered that a 32 mm Hg tissue pressure can originate this kind of ulcers. Nevertheless, a set of additional risk conditions can produce ulcers in periods of less than two hours and at lower pressures [6]. Friction and tears, which can happen during mobilization techniques on patients, increase the risk of generating these ulcers, particularly in fragile skins [7]. Oppositely, controlled and slow movements provide minor predisposition for their appearance or worsening. When a person leans on its back, pressure ulcers generally appear in the rear part of the head, in the shoulders, elbows, coccyx, heels and toes. When leaning on a side, the ulcers could appear on ears, shoulders, pelvis, hip, knees and ankle bones [7]. Other external or environmental factors can boost the appearance in other zones (humidity, non-uniformity of the support surface, etc.). More than 100 risk factors, both intrinsic and extrinsic, have been associated to these complications on the basis of the evidence gathered by personnel of assistance and infirmary [6] that are recorded in scales made to evaluate the risk of occurrence. In general, the risk of suffering pressure ulcers appears when there is no possibility of moving independently, or when movements are limited, as well as when circulatory or sensibility problems appear, and under certain conditions of nutrition and skin moisture due to perspiration, or bad conditions of care and incontinence [7]. The risk can also appear in persons older than 70 years of age, or under dry skin conditions or confusion, among other difficulties [6].

Pressure ulcers occur both in particular housings and in long-term care environments, therefore high complexity electric beds will no longer be strictly related to hospital areas but to private houses of users, with the corresponding aesthetic changes.

2.2.2 Target population

Some distinguished subgroups of high tendency to suffer secondary conditions that high complexity electric beds are capable of responding, described in point 2.2.1 are: Patients with spinal cord injuries, both traumatic and non-traumatic, cerebrovascular diseases and cerebral palsy, patients with spinal damage [8], bariatric patients and older adults. The latter constitute a group of special risk presenting a higher predisposition to suffer ulcerations and secondary complications associated to immobility, and a major risk of falls and injuries of long recovery and treatment time.

Immobility is considered to be one of the "*four giants*" of geriatrics. One of four reasons of more prominent health and disability problems in this age group [9] together with depression, memory loss, and falls (also linked with recoveries, pain, and increased time of healing). In addition to the mentioned pathologies there are diseases that affect the cognitive skills of those individuals (dementia or Parkinson's disease, for example), or those patients transitorily submitted to restrictive conditions of activity (in postoperative and healing conditions, patients with pain, etc.).

2.2.3 *Electric beds: Basic structure*

The electric bed movements originate in the materialization of the experience achieved by nurses throughout the years of treating with diverse types of patients. It started by the study of the biomechanics of the own personnel of care, which was translated to technological principles such as the biomechanical principle of foil movement, inspired by the movements of the sheets when nurses change the position of the patients.

As an example, Figure 1 shows a view in perspective of the support structure of an electric bed, with its typical functional and formal characteristics [10]. The surface of support of the patient is divided, giving place to three sections that can be driven by the patient or by the caregivers: Back, thighs and calves. As usual in this type of product, a fourth section is fixed to an end of the back and another one to the corresponding support of thighs, fixing the support of the patient to its base level. This configuration, with four sections of support, avoids significant deformations in the mattress that is in contact with the patient, even when all the mobile surfaces are in limit position, and allows a uniform distribution of pressures along waist and hip. For operation, two actuators (or a dual actuator designed for such effects) allow to drive individually the back section and the leg section (adequately articulating thighs and calves). The movement of the leg section allows slight elevations, as well as descents -already in recent models- achieving chair positions and support for the removal of the equipment [11, 12].

The elevation of the support level of patients constitutes a problem that acquires special importance when they risk of suffering falls, both when trying to enter or exit the bed, as well as due to possible confusion or ignorance of the environment that can afflict them. This allowed the appearance of a segment of "low beds" in the market, created to prevent those problems, accompanied by other means of monitoring and control, among other equipment. Likewise, it turns suitable for the medical and support personnel to be able to rely on means that set the elevation of the patient, according to the different instances of treatment or care, as well as on ergonomic aspects of managing the patient and the product, consequently facilitating these tasks. Beside of having retractable siderails, electric beds can have active means to control the elevation of the base level of the patient, through actuators that mobilize "scissor" type mechanisms or through one or more extensible columns of controllable elevation (see Figure 1). Additionally, in case of having two (or possibly more) independent elevation mechanisms over the surface of support, the selective control of these allows to achieve specific positions as cardiac chair or Trendelenburg, which depend on changes in the inclination of the whole surface of support of the patient.

The distinctive parameters of these structures reached typical and accepted values consolidated by procedures that arose along their development and expansion, in the form of requirements on properties entailed for these products, in terms of dimensions, functioning, performance and safety [13]. In general, the frames of these beds measure 1.00 m of width and 2.00 m of length, and admit elevations between 0.40 m and 0.80 m for the base support level of the patient (independent to the thickness of the mattresses). The sections of the back support admit angles of up to 70 ° for its positioning. In particular, the mechanical conditions of the siderails are regular, to minimize risks of trapping and injuring during equipment operations, as well as of accidents such as those detected throughout the years [14].

At the end of the timeframe of interest of this study, and as functions were consolidated in different products, advanced versions of medical beds pointed at the incorporation of additional mechanisms of mobilization on this basic structure, valuable for improving patient care.

Figure 2 shows a patent scheme that presents the biomechanical principle of corporal rotation, directed to the mechatronic bed developed at the University of Buenos Aires [15, 16]. This product shows advanced virtues for the prevention of health conditions derived from immobility, as those mentioned in section 2.2.1. The figure details the lateral surfaces that can be driven to adopt multiple positions, by additionally supporting the regular control functions available for the support surface of the patient.

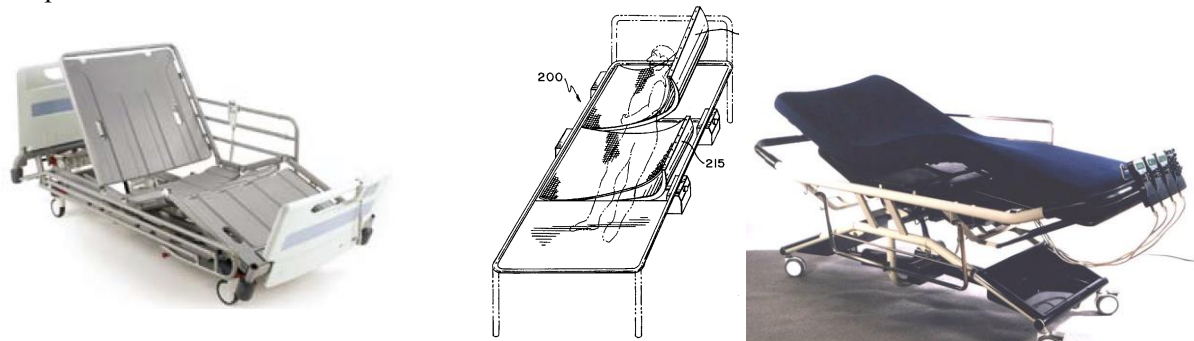


Figure 1. View in perspective of a high complexity electrical bed [10], with 4 sections a support surface and elevation control.

Figure 2. Left: View of the support structure of the patented biomechanical principle of corporal rotation [16]. Right: High complexity mechatronic bed model AC2000 with corporal rotation, developed by CIDI-FADU-UBA (*Centro de Investigación en Diseño Industrial de Productos Complejos*) [15, 17].

Electric beds, together with the complex technical difficulties for movement implementation and integration, software and communication of the patient with the environment, must respond to a set of socio-economic, political and aesthetic problems. The latter were also considered in the survey carried out in the proposed timeframe for the product shown hereafter.

2.3. Evolution and innovation

Hereby, we present the development of electric beds for hospital and household attention, following a determined time line (based on the date of submission of patents and inventions, and publication of related articles in magazines and newspapers). Only those products that were examples and marked innovation trends considered relevant along the 20th century were selected for this survey. The chronology was subdivided in three stages: early electric and semi-electric beds of the 40's to mid-70's; mechatronic beds in general; and from 2000, intelligent mechatronic beds. As any other subdivision, the present proposal is arbitrary and does not impose neither strict limits nor temporary rigid barriers. The most advanced interactivity (environment-patient) in use, the incorporation of software into the electromechanical functioning of mechatronic beds, and for the intelligent mechatronic beds, the incorporation of all sensors, interfaces and communication devices in a wide sense, was included as criteria, considering that they are fundamental for gathering information of the patient in real time.

The first half of the 20th century offers examples of electric beds with diverse functions. Figure 3a) shows an example of a hospital bed, designed to be controlled by means of a push-buttons panel. In addition to the control of the basic functions of the bed (as elevation of the support and legs section) there are many surprising and actual resources considered in this survey: Retractable sink, warm and cold water flow, control of lights and blinds, as well as the automation of the patient's residues disposal [18]. The electric beds with basic functions, formally closer to those pointed out in section 2.2.3, will progress globally [19], and advance into more options with additional functions such as Trendelenburg control and the total elevation of the surface of the patient (a tempting issue since late 40's [20].

Between 1946 and 1950 patents and inventions of equipment with additional functions and alternative actuators (height, Trendelenburg and oscillatory movement controls) were submitted. En 1946, Howard Hughes, after a plane accident and unsatisfied with the available equipment, created a hospital bed adapted to his needs, with 6 sections and 30 electric engines, and cold and hot water flow. In 1949, patents of interface of actuators, with control and basic functions, appear. In the 50's, the Hill-Rom Company, presently one of the most important enterprises, developed its first bed with electric engine (1952), and commercialized its first bed with full electrical functioning (1956) [21] (see Figure 3b)).

The decades of 1960 and 1970 were characterized by an increasing demand of medical attention, stimulating progress towards health services external to hospital care (community and residential health services) [22]. Other remarkable characteristics were the emerging incorporation of computers for information storage and processing, including the debate in regard to its potential and relevance, and the use of telecommunications for its transport to long distances [23] and centralized monitoring (incipient second stage). During these years, alternative models for high complexity care conditions appeared, such as the Circ-O'lectric Bed developed by Dr. Homer Stryker in 1958 [24], of general use between the late 50's and late 70's (see Figure 3c)). This remarkable design allowed the patient and person in care to control corporal rotations according to specific needs by means of electric actuators. Figure 4a) shows the first electric bed built and commercialized in Japan in 1962, illustrating the Far East market expansion [19].

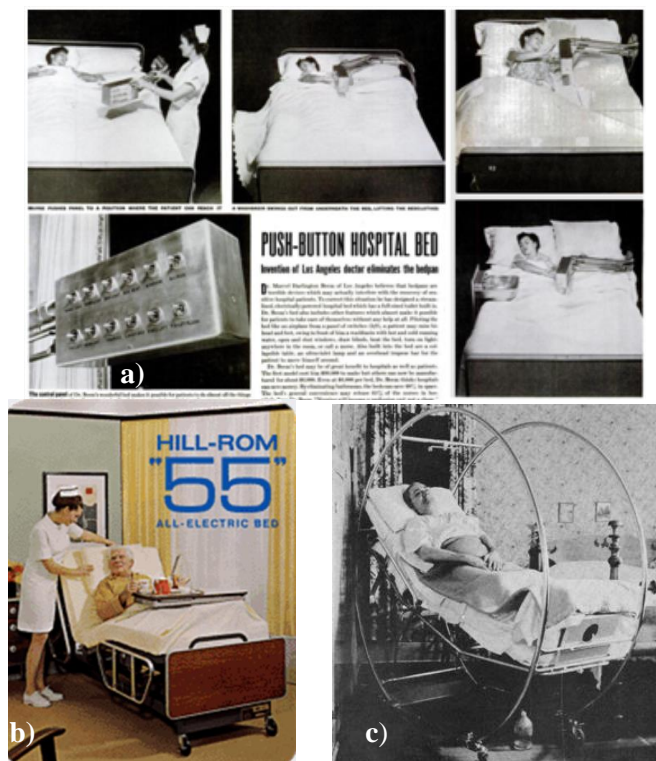


Figure 3: a). Push button hospital bed by General Electric, 1945 [18]; b) Hill-Rom's first bed with electric engine, 1952 [21]; c) Circ-O'lectric Bed, Stryker Company, 1958 [24, 25].

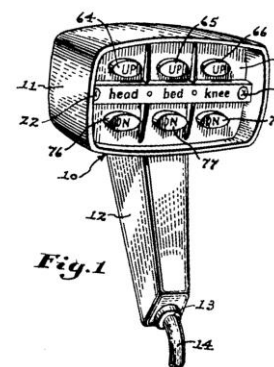
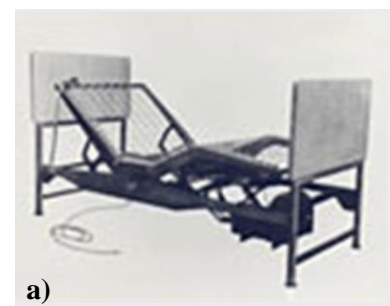


Figure 4 a). Bed built and commercialized in Japan, 1962 [19]; b) Patent of 1961, showing basic bed controller, with three functions [26].

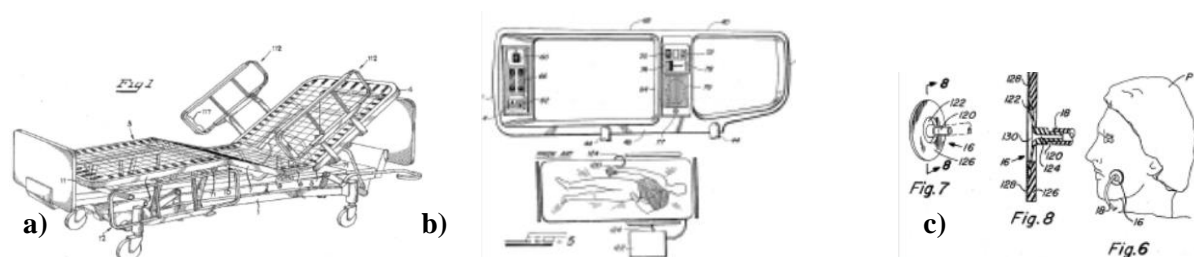


Figure 5 **a)** Image of a 1974 patent showing control panels on siderails [27]; **b)** Image of 1978 patent incorporating siderail controls for remote electrical devices [28]; **c)** 1980 patent that includes alternative means for personnel call [29].

From 1976, the evolution of beds is affected by the first medical devices regulation system (Medical Device Regulation Act). In 1977, the International Electrotechnical Commission published the IEC 60601 standard for medical electrical devices [4].

Between 1970 and 1979, beds in all hospitals incorporated siderails with side control panels, and some versions incorporated external equipment control (see Figure 5a) and 5b)). The incorporation of siderail control panels with increasing and variable functions, as expressed today, commenced in the decade of 1970 [21, 27] (see Figure 5b). Even when the debate on possible risks associated to these protections still remains [30]. Figure 5 shows a patent with the description of communication and detection means of a bed of those times. The first mattresses for preventing pressure ulcers appear. Attention outside hospitals is stimulated by promoting hospital beds for home use (see Figure 6a). In the 80's, there was an evolution and proliferation of patents of active and passive therapeutic mattresses, including models with built-in position detectors for the disabled, as well as mechanisms for weighing the patient while leaning in bed. Until then, remote controls were wired. Nowadays, this kind of control is offered as alternative. Patient-exit monitoring and control of external devices from the bed also appears as a concept in development in patents of this decade [28, 31]. The decades of 1980 and 1990 witnessed an exponential growth of medical care devices, including some models that became market icons (see Figures 7a and 7b). Permanent cardiovascular monitoring became common features in hospitals, and treatment was affected by technological progress [4].

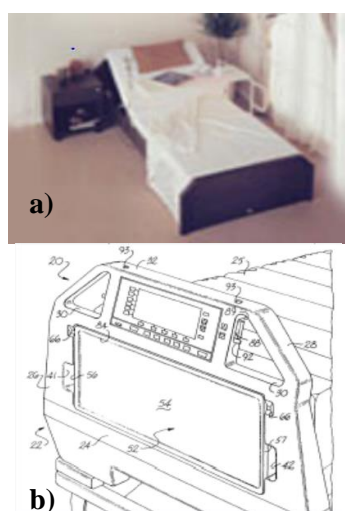


Figure 6. **a)** Electric bed for home use, 1983 [19]; **b)** Patent graph showing innovations in the front panel, 1993 [32];

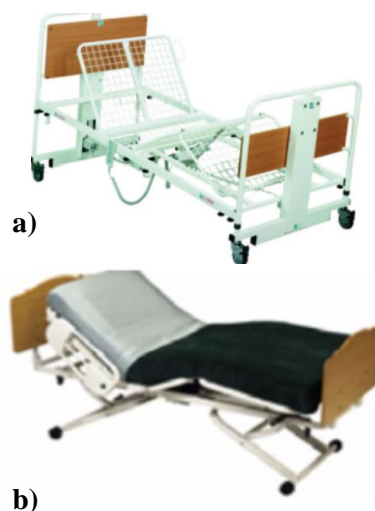


Figure 7. **a)** Sidhil Millenium Community Bed model, 1990 [22]. **b)** Joerns UltraCare model, 1999 [33].

Patents of the 80's show the interest in including means to weigh patients, avoiding their exit from the bed (see Figure 8), using incorporated or detachable control instruments. Other patents include alternative nurse-calling means for disabled patients [29] (Figure 5c)) and the monitoring of their position and bed exit, as well as special active and passive mattresses [34, 35].

During the 90's, more beds with varied and advanced mechanical functions appeared, such as the possibility of sitting in a chair position to exit the bed, visible in the Hill-Rom Total Care model of 1998 [11] (Figure 9). A domestic example is the mechatronic bed developed by the Industrial Design Research Center of the University of Buenos Aires (*Centro de Investigación en Diseño Industrial, Universidad de Buenos Aires*) [17].

At this time, mechatronic beds are a reality, and further technological and integrational advances allow consolidating the progress towards "intelligent" and integral equipment, with monitoring and advanced services, and integrated to accessories like active mattresses, under a unique control panel. The development of voice control as a potential advantage is mentioned in a 1991 patent, described as an environmental control unit for the hospital bed and its surroundings [36]. The effectiveness of voice recognition systems available in the 90's was limited if compared to present solutions, but its potential is still significant.

Concerning regulations on medical devices, the Council Directive 93/42/CEE on medical devices [37] appears in 1993, and the first particular standard for electrically operated hospital beds is published (60601-2-38:1996) [13], indicating the special care and relevance that this type of products, of increasing capacity and complexity, deserve in the context of medical electrical devices. Subjects covered by this standard included protection against electrical and mechanical hazards, electromagnetic compatibility, as well as indications and requisites for controls, stability, accuracy of operations and fault-condition tests. Towards the end of this timeframe, in the year 2000, the additional European standard EN 1979, was published. This standard regulated adjustable beds for disabled patients, under home-care environments [38]. Later on, the current ISO/IEC-approved particular standard, 60601-2-52, would be published in 2009 and enforced in 2013, integrating both prior standards, and dealing with basic safety and essential performance of medical beds, under a broad range of application environments (from hospital to homecare) and based on a new theoretical background, resulting in updated reference values and requisites [39].

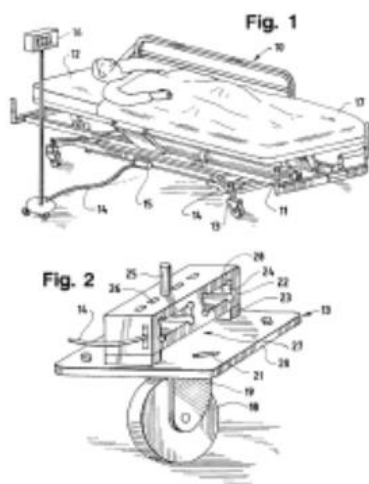


Figure 8. Images of a 1994 patent showing a weighing scale included in the wheels [40]



Figure 9. Hill-Rom Total Care model of 1998 [11].

3. Conclusions and future perspectives: Mechatronic beds of the 21st century

The analysis of this first historical progression of high complexity hospital beds allows outlining conclusions about elements that direct and determine growth and changes in these equipments:

- Many functions found in state-of-the-art automatic beds corresponds to counterparts found in their origins: from basic mechanical functions up to concepts like monitoring bed exit, communication with caregivers, and specific proposals for the care of critical patients or with variable disabilities. All of these are found throughout the mentioned timeframe, both as specific products as well as on registered inventions.
- The increasing "delegation" of tasks on this type of equipment is manifest, in line with the growth of the demand and the changes in the structure of the health system, and provides means for easing the work of the caregivers and, when possible, facilitating the autonomous care of the patient.
- There is a growing specificity in different models of electric medical beds, with morphologic, functional and aesthetic aspects orientated to specific environments and populations (intensive care in hospitals and domiciliary care, for the elderly, pediatric, bariatric patients, etc.)
- Finally, there is a remarkable trend towards relocating and re-discovering new implementations for the increasing range of technologies in dispersion. This trend will shape the advances for current market demands, such as: inclusion of tactile interfaces, functions of connectivity and complex real-time monitoring, as well as of new sensors and actuators, together with enhanced signal-processing capabilities. These elements allow the creation of new and improved versions of these devices, making available novel means for developers to propose new variants of added value for this family of products (focused in the experience of the user), while preserving the equipment's basic functions. This synthesis and technological growth has changed the visible face of the market of high complexity mechatronic beds in the last decades.

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