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REVIEW

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State of the art of immobilization designs for the conservative treatment of bone fractures (1982 – 2025) – a patent review

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ABSTRACT

Introduction: Bone fractures represent a global health problem with the incidence of fractures on the rise each year. The predominant method for addressing bone fractures involves immobilization. Worldwide, many initiatives have sought to develop innovative fracture immobilization designs, and numerous solutions have been patented. However, a comprehensive overview and systematic classification of these patented designs is lacking.

Areas covered: In pursuit of these patented immobilization designs, the Espacenet database, recognized as the largest global repository of patents, served as the principal investigative tool. Using a search string, patent classifications and inclusion criteria a total of 71 patents were identified. These can be classified into four unique design groups: (1) fixed and partly enclosed, (2) fixed and fully enclosed, (3) adjustable and partly enclosed and (4) adjustable and fully enclosed designs. The designs that are commercially available are predominantly situated within groups 3 and 4.

Expert opinion: Advances in 3D scanning and additive manufacturing could improve comfort, personalization, and monitoring in fracture immobilization, but clinical adoption is hindered by slow production times, workflow misalignment, and regulatory barriers. Key improvements are needed in scanning accuracy, adjustment protocols, and integration into hospital logistics to ensure both technical feasibility and clinical usability..

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KEYWORDS
Immobilization; patent; design; classification; additive manufacturing

1. Introduction

1.1. Background

In public health, bone fractures are a major issue. Globally, there has been an increase of over 33% in fractures between 1990 and 2019, with 178 million new fractures reported in 2019 [1]. A bone may be completely fractured or partially fractured in various ways, and fractures in older adults account for the majority. Older adults have a reduced mineral density of the bone due to hormonal consequences of aging. If this process continues, it can lead to osteoporosis. In addition, older adults are more likely to fall due to vision impairment, reduced reaction times, and reduced muscle mass [2].

The most common causes of fractures are (1) trauma, such as falls or accidents, (2) osteoporosis, a disorder that weakens bones, and (3) overuse, where repetitive motions put too much force on a bone [3]. There are two main approaches to treat bone fractures: conservative and surgical. Both approaches include immobilization of the injured body part. In surgical treatment, immobilization follows the intervention, while in conservative treatment it is the main therapeutic strategy. The purpose of immobilization is to allow the fracture to heal and to reduce pain. Depending on the type of fracture, immobilization can last from days to several months. For example, the average immobilization duration is four to six weeks for a distal radius fracture, the most commonly broken bone in the arm. Longer immobilization periods also occur, such as 12 weeks for a scaphoid fracture [4] and in rare cases even this period is not long enough for fracture union [5].

Fractures can lead to work absence, decreased productivity, disability, reduced quality of life, health loss, and high healthcare costs. They are therefore a major burden to individuals, families, societies, and healthcare systems [1].

1.2. Current challenges

The immobilization of the fractured body part facilitates bone healing, but it is not without complications. The most common are skin irritation and maceration, pressure sores, thermal burns, soft tissue swelling, and cast saw injuries [6]. Prolonged immobilization may lead to joint stiffness, muscle atrophy, cartilage degradation, ligament weakening, and osteoporosis [7]. Substantial declines in skeletal muscle mass can already occur after only five days of immobilization [8]. This can result in longer recovery times, and in older patients, sometimes in incomplete recovery [9]. Immobilization of the hand for more than six weeks is associated with decreased hand function, reduced range of motion, lower grip strength, and higher pain scores [10]. Metacarpal fractures, the most common hand injuries, typically require immobilization of around four weeks [11].

Infectious complications after cast and splint application are rare but may lead to moist padding and skin breakdown [12]. More serious complications include deep vein thrombosis and compartment syndrome, the latter potentially life-

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Article highlights

- A structured search of the Espacenet database identified 71 patents related to fractureimmobilization devices, providing the first systematic mapping of patented design concepts in this domain.
- Patent analysis revealed four unique design categories – fixed/partly enclosed, fixed/fully enclosed, adjustable/partly enclosed, and adjustable/fully enclosed – offering a reproducible framework for classifying immobilization technologies.
- Review of emerging technologies indicates that 3D scanning, additive manufacturing, and sensor integration have potential to enhance fit, monitoring, and functional adaptability, but current limitations in scanning precision, production misalignment with hospital workflow, and regulatory pathways restrict clinical implementation.
- Future development is likely to favor modular, partially customizable immobilization systems, dependent on improved workflow integration, validated adjustment protocols, and evidence from controlled clinical studies assessing safety, performance, and costeffectiveness.

threatening [7]. Healthcare workers are also at risk, for example through respiratory sensitization caused by inhalation of chemicals from synthetic casts [13].

In addition, the environmental impact of current immobilization solutions is a growing concern. Their non-recyclability leads to large amounts of medical waste [14]. Proper disposal of synthetic casts and upcycling of cast material, including plaster of Paris, is challenging due to their toxic ingredients and nonbiodegradable nature [6]. Although synthetic and biobased casting materials are increasingly used, plaster of Paris – first introduced in the 1800s – remains in use, particularly when careful molding is required [15].

1.3. Goal

Worldwide, many initiatives have sought to develop innovative fracture immobilization designs, and numerous solutions have been patented. However, a comprehensive overview and systematic classification of these patented designs is lacking. This knowledge gap makes it difficult for clinicians, researchers, and medical device developers to assess the range of existing technical solutions – such as adjustable mechanisms using velcro, pneumatic or fluid-based systems – and to understand broader design choices, such as fully enclosed versus partly enclosed immobilization devices. This study addresses this gap by providing a structured classification of patented immobilization devices, based on their intended application and functional design characteristics.

2. Methods

2.1. Patent search strategy

A structured patent search was conducted in *Espacenet* (European Patent Office; accessed August 2025), which provides access to over 150 million patent documents from more than 100 countries dating back to 1836. The search was restricted to English and international (WO) patents, i.e. national patents that had progressed to the international phase through the World Intellectual Property Organization (WIPO). The search was guided by the International Patent Classification (IPC) system, which categorizes patents into technical fields. For this study, the main group A61F5 was selected, corresponding to 'orthopedic devices for non-surgical treatment of bones and joints' within the broader category A61 ('Medical or veterinary science'). Patents were identified using the following search string: (ta all 'cast' OR ta all 'splint' OR ta all 'brace') AND (ta any 'immob*' OR ta any 'fracture') AND ipc any "A61F5"where *ta* refers to title or abstract. Filters were applied for English-language (EN) and World (WO) patents. This search yielded 149 unique patent documents.

2.2. Eligibility criteria and selection

The scope of the review was limited to noninvasive immobilization devices for bone fractures in human extremities. The selection process was conducted in a structured, stepwise manner inspired by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework. Although PRISMA was originally designed for systematic reviews of scientific literature, its principles were adapted here to enhance transparency and reproducibility in the identification and screening of patents. Exclusion criteria were patents describing veterinary applications, dental applications, invasive devices, devices without an immobilization function, or devices not intended for upper or lower extremities. After applying these criteria, 71 patents remained for further analysis (Figure 1). These patents were analyzed in terms of application and function.

Some patented designs fully enclose the injured body part and others partly enclose it. Some designs are adjustable, and others have a fixed fitting on the patient's body. These properties were used to place the found patents into four unique design groups (Figure 2):

- fixed and partly enclosed designs,
- fixed and fully enclosed designs,
- adjustable and partly enclosed designs,
- adjustable and fully enclosed designs.

2.3. Assessment of market availability

To evaluate the translation of patented concepts into clinical or commercial practice, the 71 included patents were further screened for ownership by commercial entities. This resulted in 36 patents. The websites of the corresponding companies were examined to determine whether the patented devices were available as marketed products. For each available product, the corresponding commercial name was recorded. This process identified 25 patented immobilization designs that were commercially available at the time of the study.

2.4. Ethical considerations

All patent documents analyzed in this study were obtained from the Espacenet database, which provides access to publicly available information in the public domain. No confidential data, human participants, or animals were involved; therefore, ethical approval was not required.

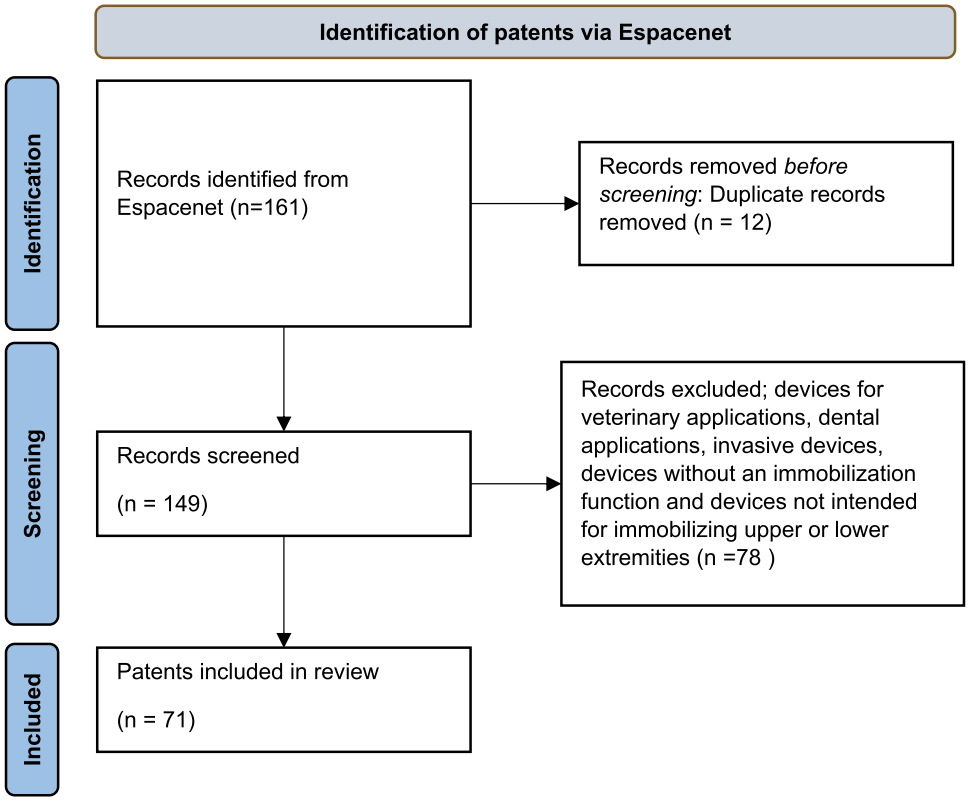


Figure 1. Patent identification process flow.

3. Results

3.1. Overview patented immobilization designs

After the identification of the designs, alle designs were place in four unique design groups (Appendix A). The application and the functional design is analyzed and discussed per design group.

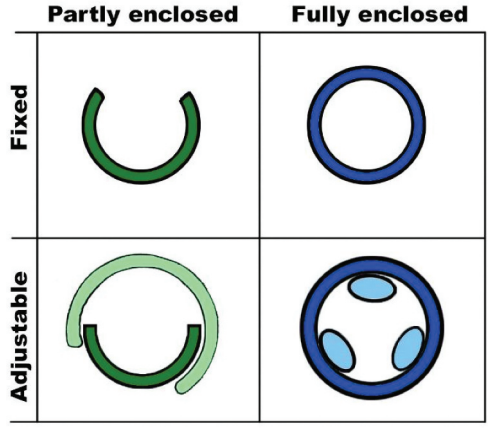


Figure 2. Patent classification in four unique design groups. In the designs the fixed and partly enclosed part is indicated in dark green, the adjustable part if applicable of the partly enclosed designs is indicated in light green. The fully enclosed designs are indicated in dark blue and the adjustable part if applicable of the fully enclosed designs is indicated in light blue.

3.2. Fixed and partly enclosed designs (group 1)

3.2.1. Application

The first group of patents consists of nine distinct designs, six can immobilize upper and lower extremities [16–21] and three designs are tailored for specific applications, like finger fractures [22] (Figure 3), wrist fractures [23] and pediatric femoral fractures [24]. Adult finger fractures and pediatric femoral fractures both typically require an immobilization period of 4–6 weeks [6].

3.2.2. Functional design

Eight designs are prefabricated [17–24] and one design is customized during the application [16]. Four prefabricated designs are ready to use and need no further adjustments [20–22,24]. The design of Nsubuga [24] aims to minimize the discomfort of the patient that typically wears the splint for six weeks using compartments that can be filled with air or liquid to reduce pain and pressure sores. The prefabricated designs of Allenberg [17], Singh [18] and Krajewski [23] are made of thermoplastic materials. These designs are warmed before application so they can be molded around the injured limb of the patient. When the thermoplastic materials cool down they become rigid and immobilize the injured limb. The design of Schuind [19] is also prefabricated, using additive manufacturing (AM) as a production method, and customized, based on a scan of the injured limb. The feasibility of prefabrication, as advocated by Schuind [19], emerges as a promising avenue for streamlining the application process, particularly benefiting patients with conditions like Parkinson's disease. This underscores the multifaceted considerations in designing effective and patient-friendly limb immobilization solutions.

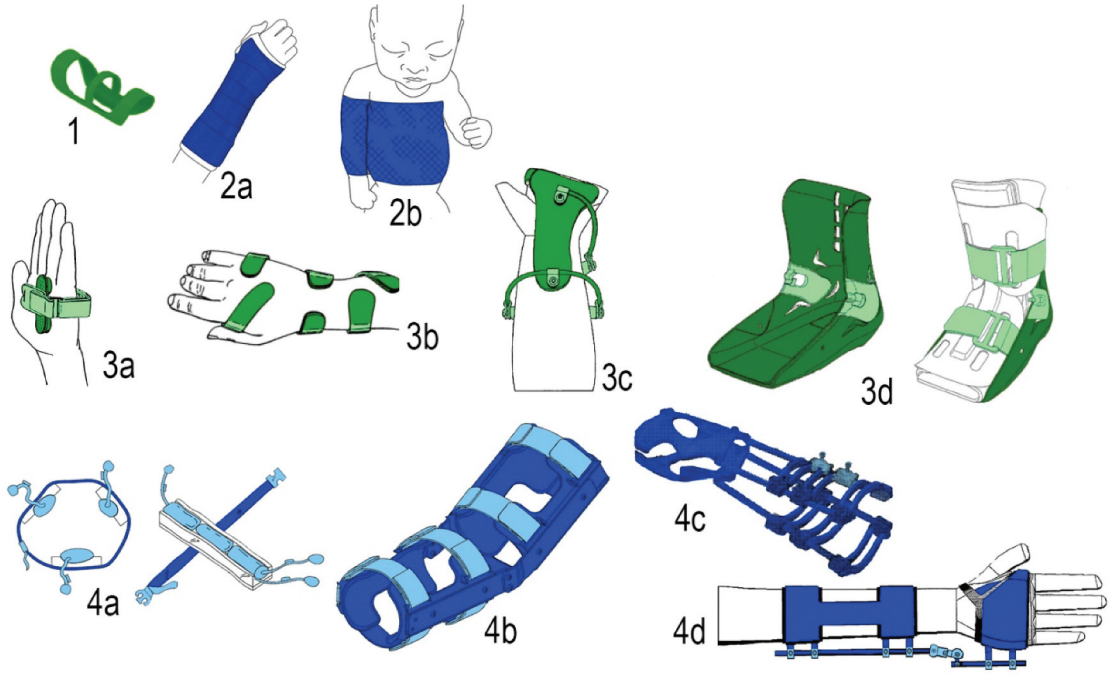


Figure 3. The first group shows a fixed and partly enclosed patented immobilization design. Figure adapted from Starkey [22]. 2.2 The second group shows two fixed and fully enclosed immobilization designs. The design of Evans [39] (2a) can be used to immobilize fractures in both upper and lower extremities. The design of Quist [27] (2b) can be used for an infant collar bone fracture. Figures adapted from (2a) Evans [39] and (2b) Quist [27]. The third group shows three adjustable and partly enclosed patented immobilization designs. The designs contain rigid parts (dark green) and can be adjusted with adjustable elements (light green), like straps (3a), flexible material (3b), bolts and knots (3c) or a combination of straps and air (3d). Figures adapted from (3a) Viegas [47] (3b) Danemen [52] (3c) Kumar [63] and (3d) Pick [65]. The fourth group shows adjustable and fully enclosed patented immobilization designs. The adjustable parts are depicted in light blue, the parts that fully enclose the patient's limb are depicted in dark blue. Adjustability in the designs is incorporated using air (4a), straps (4b) rails (4c) and bolts and knots (4d). Figures adapted from (4a) Manoach [82] (4b) Cheng [71] (4c) Dharmalingam [70] and (4d) Pomeroy [74].

3.3. Fixed and fully enclosed designs (group 2)

3.3.1. Application

The second group consist of twenty fixed and fully enclosed immobilization solutions [25–44] showcasing a spectrum ranging from versatile applications for upper and lower extremities. Of this group only one design was developed specifically for the immobilization of broken collar bones of infants [27] (Figure 3).

3.3.2. Functional design

Nine designs are customized during the application on the patient [30,31,33,35–40]. Liddle's design was made of a thermoplastic material to immobilize a finger or an arm [33]. Honeycutt [37] and Evans [39] used soft cast material that is wrapped around the fractured limb (Figure 3). Evans uses material that is radiolucent and does not disintegrate on removal preventing irritating dust for the patient and clinician. Five of the customized designs that are wrapped around the fractured limb contain multiple layers from different materials to optimize the characteristics of these different materials [30,31,35,36,38]. Nelson [31] and Jorissen [35] incorporated multiple layers from different materials in a sealed enclosure that can be wrapped around the fractured limb to save application time.

Six designs are prefabricated and ready to use [25,27,28,41–43]. The design of Tadic [41] was made of a spiral of unrusting tin for the fitting on the patient that hold stiff flat sticks for immobilization. Chhatrala [25] designed a customizable prefabricated cast that contains hollow tubes that can be injected with an infusion material to optimize the fitting. The material hardens after infusion, so the immobilization design becomes rigid. The design of Grabowski [28] consists of a flexible sleeve of two layers that is put on the patient's injured limb. The material of the sleeve is hardened using an UV lamp. Two prefabricated designs incorporate elasticity to help placing the brace on the fractured limb [27,41] And two prefabricated designs are made of thermoplastic materials [42,43].

Five designs were personalized, tailor made designs [26,29,32,34,44]. The design of Sethuraman et al. [29] was made via AM and contains two rigid parts that are hold together with velcro tape around the patient's limb. Two designs [26,34] are tailor-made using a 3D scan of the fractured body part. These tailor-made designs of Janzing [26] and Muñoz [34] include various suggestions for the manufacturing of the design including Stereolithography (SLA), Digital Light Processing (DLP), Fused deposition modeling (FDM), Selective Laser Sintering (SLS), Selective laser melting (SLM) and Electronic Beam Melting (EBM). Moreover, the integration of elasticity, AM and sensor technology, as seen in designs by Sethuraman [29] and Muñoz [34] not only exemplifies advancements in immobilization techniques but also offer solutions to optimizing patient treatment with enhanced monitoring capabilities.

In conclusion, the versatile array of fixed and fully enclosed designs examined here highlights a diversity in approaches, from customized solutions with multiple

material layers and personalized prefabricated casts to innovative applications of materials like thermoplastic and soft cast.

3.4. Adjustable and partly enclosed designs (group 3)

3.4.1. Application

The third and most extensive group in focus comprises twenty-five adjustable and partly enclosed immobilization designs [45–69]. Of this group eleven designs support the treatment of hand, wrist or finger fractures [45–55]. Eight designs can be widely applicated [56–63], two designs can be used for fractures of the lower extremity [64,65] and four designs are designed for a specific application, like for the shoulder [66,67] the clavicula [68] and humeral fractures [69]. The design of Viegas [47] (Figure 3) is a minimalistic design that immobilizes the metacarpal fractures and aims to preserve the hand function as much as possible during the immobilization. The design of Pick [65] is developed for the immobilization of the lower leg while allowing the patient to walk in order to reduce the recovery time. The design of Torrens [62] can also incorporate a pressure sensor offering a monitoring function for the fitting of the design. During the healing of the bone fracture the swelling of the limb reduces. Due to the muscle atrophy, the circumference of the injured limb also decreases, which would mean that the immobilization device becomes loose, therefore many designs are adjustable.

3.4.2. Functional design

Eighteen designs have an adjustable fit [45,47–61,64,65]. Six designs can adjust the position of the immobilized limb and also have an adjustable fit [46,62,66–69]. The design of Kumar [63] has not only and adjustable fit and an adjustable position but can also allow for some degree of movement claiming this can promote the healing of the fracture. In the early stages of the healing of a bone fracture the limb is usually swollen. Most designs use straps like velcro tape for adjustment, like the design of Jaccard [46]. Danemen's [52] design is made of bendable aluminum which makes it easy to apply (Figure 3). Pick [65] uses inflatable elements in his design to adjust the pressure on the limb (Figure 3). Two designs [66,67] allow adjustment of the limb position before or during immobilization. Like the design of Lemmon [67] where the position of the limb can be adjust using spacers and velcro.

The design of Summit [59] which has only an adjustable fit, uses an elastic material for the adjustment. Florek [68], Jaccard [46], Lemmon [67] and Turconi [66] all use belts adjust the position of the injured limb. Their designs can be used for broken shoulders or a broken clavicle. Bai's design [56] uses airbags and straps and includes an inflation device to adjust the fitting. The design of Kumar [63] offers various options for the fabrication of the design that can be made using a rachet type mechanism, rails, clamps, bolts and knots to adjust both the fitting as well as the position of the designs of the injured limb. The design of Lofti [54] uses a scan of the injured limb but makes a 2D scan which, he claims, is quicker to make and cheaper as well. This scan is used to make cut a personalized model from a thermoplastic sheet which can be molded after the material is warmed on the injured limb of the patient. All designs are prefabricated.

In conclusion, the diversity within the adjustable and partly enclosed designs reflects a nuanced approach to limb immobilization, addressing specific fractures like in the hand and wrist. The adaptability of these designs, utilizing adjustable straps, belts, airbags and innovative materials such as thermoplastics and bendable aluminum, underscores a commitment to accommodating changes in limb size during the healing process. The exploration of functional designs shows a commitment to enhancing patient comfort and mitigating complications, and the potential of prefabrication.

3.5. Adjustable and fully enclosed designs (group 4)

3.5.1. Application

The fourth group offers eighteen adjustable and completely enclosed immobilization designs. Of this group, sixteen designs can be used for fractures of the lower and upper extremities [70–86], two designs have a specific application, like the design of Nelson [86] for wrist and arm fractures and the design of Anderson [87] for fractures below the knee.

3.5.2. Functional design

Thirteen adjustable and completely enclosed immobilization designs allow for the adjustment of the fitting, needed due to swelling reduction [72,73,75–82,84–86] and five designs allow for the adjustment of the fitting and the adjustment of the position under which the injured limb is immobilized [70,71,74,83].

The subfunction adjusting was incorporated in the designs using; (I) only straps or belts [73,80,85], 86](II) only screws, bolts and nuts [74,75,81], (III) inflatable compartments and straps [76–78,82–84] or (IV) combination of these mechanisms like rails, screws, bolts and nuts combined with straps or belts [70–72,79,87] (Figure 3). One design uses special designed fasteners [81]. All designs were prefabricated. Notably, the incorporation of diverse mechanisms, including straps, screws, inflatable compartments, and combinations thereof, demonstrates a commitment to adaptability in response to factors like swelling reduction and changing limb conditions during the healing process. In conclusion, the adjustable and completely enclosed designs within this group offer a spectrum of features, addressing the need for fitting adjustments, limb position alterations, or a combination of both.

3.6. Market availability

To gain insights into the market availability of patented designs, we conducted an analysis, which resulted in an overview of commercially accessible designs. Notably, a substantial majority, 36 of a total of 71 patented designs, originate from corporates, highlighting a significant corporate presence in the patented design landscape. Of the 36 corporate patented designs, 25 are currently commercially available (Figure 4). Looking into the specifics, most of these commercially accessible designs fall under the adjustable classification, comprising ten partly enclosed, adjustable designs, which are classified within group 3, the largest group of patented

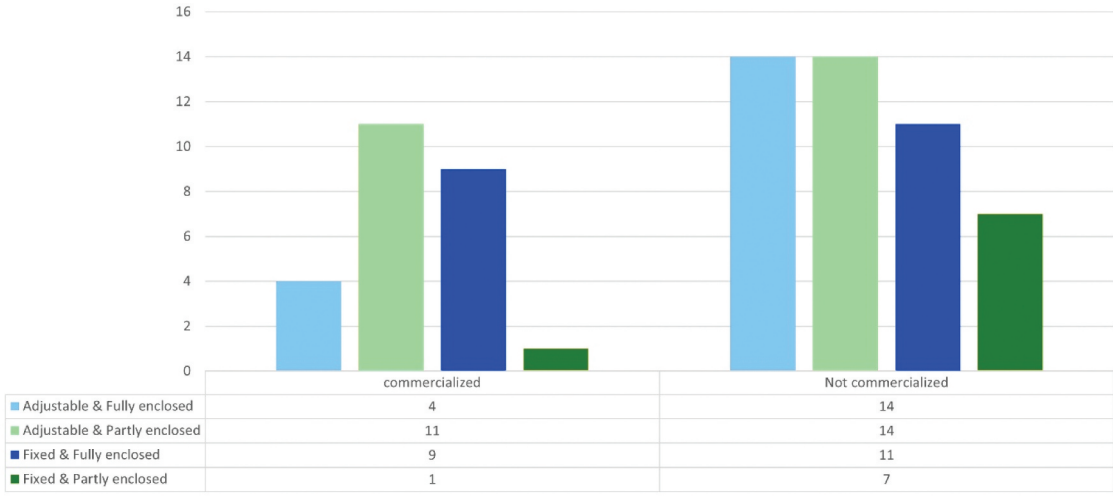


Figure 4. Overview of the commercialized and not commercialized patented immobilizations designs per design group.

immobilization designs. Additionally, seven fully enclosed and fixed designs, classified under group 2. Further examination reveals that four fully enclosed and adjustable designs classified under group 4 also contributing to the variety of immobilization solutions commercially accessible. One design belonging to group 1, characterized by a fixed and partly enclosed nature, is commercially available. This breakdown highlights not only the dominance of corporate entities in patent filings for immobilization designs but also provides an insight into the current market offerings, showing a prevalence of adjustable designs. The active period of a patent can be up to 20 years if the patent holder pays the annual fee. Nineteen of the twenty-five commercialized patents are still active (Table 1). The patent owner of an active patent can decide who can use the patented design and how. Also, he can prevent third parties from exploiting the patented design commercially. Meanwhile, hospitals and universities collectively account for 14% of the patented designs, underscoring a smaller but still impactful presence.

4. Discussion

This study analyzed patented immobilization designs for fracture treatment to examine their evolution over time and the factors influencing these changes. Three key findings were identified: (I) partly enclosed designs (groups 1 and 3)

Table 1. Overview of the commercially available patented immobilization designs. Designs marked with an * are still active according to the information of the Espacenet database.

Patent title	Commercial product name	Ref.	Year	Design group
Splint	Easy-Fit Finger Splint™	[22]	2017*	Partly enclosed and fixed (group 1)
A breathable and customized cast for immobilization of fractured limb	FlexiOH®	[25]	2016*	Fully enclosed and fixed (group 2)
Soft cast material	Delta-Cast® Soft	[39]	2005*	
Moldable injury therapy device and method	Delta Dry Cast™	[35]	2012*	
Curable immobilizing cast dressing	UV Cast™	[28]	2023*	
Splint using thermoplastic resin fabric and manufacturing method therefor	Qplint	[42]	2017*	
Production of a custom medical splint or brace for immobilization of a selected region of a patient's body part	Swibrace™	[44]	2020*	
Orthopedic splint	Ortho-Glass	[40]	2006*	
Adjustable wrist and hand splint	Royce Medical Wrist brace™	[45]	1990	Partly enclosed and adjustable (group 3)
Thumb brace	Exos Extended Short Thumb Spica	[51]	2020*	
Wrist brace	ProCare Aluminum Finger Splint Set	[52]	1994	
Curable splint for orthopedic use	Hygia Belt Splint™	[61]	2014*	
Functional cast therapy product and method	FCT (Functional Cast Therapy) Starter Kit™	[60]	2015*	
Orthopedic shoulder device	Aircast® Quick-Fit Shoulder Immobilizer	[67]	2015*	
Brace for immobilizing a traumatized or operated shoulder	Omoplus 2.0™	[66]	2015*	
Orthopedic walking brace having a curved sole	ProCare XcelTrax® Ankle	[64]	2014*	
Walking brace	Aircast® AirSelect™ Elite	[65]	2005*	
Splint	Zero-Cast™	[63]	2014*	
Immobilizing and supporting inflatable splint apparatus	Orthoflex™	[77]	2005*	Fully enclosed and adjustable (group 4)
Orthopedic system for immobilizing and supporting body parts	Exos® Pediatric Short Arm Fracture Brace – Open Thumb	[79]	2008*	
Brace for fixation of bone fractures	Rebound® Post-Op Elbow	[73]	1991	
Fracture brace	Aircast® wrist brace	[76]	2006*	

emphasize air circulation to reduce adverse skin effects; (II) most patents fall into the adjustable classification (groups 3 and 4), underscoring adaptability as a central design principle; and (III) a recent increase in fixed, fully enclosed designs (group 2) coincides with the adoption of additive manufacturing (AM) technologies.

4.1. Air circulation in partly enclosed designs

Groups 1 and 3 consistently prioritized ventilation to mitigate skin complications commonly associated with traditional plaster casts. Zolfagharian et al. [14] mention breathability as a benefit of 3D printed orthosis that use holes for air circulation on the skin. This analysis demonstrates the persistence of this design driver in patent activity, underscoring its clinical relevance.

4.2. Adjustable immobilization designs

Groups 3 and 4 dominated the dataset, reflecting the importance of adjustability for accommodating swelling and enhancing comfort. Chen et al. [88] have also emphasized the role of adjustability in postoperative care. By showing its prevalence in patents, this study highlights adaptability as a recognized competitive advantage in device development [89].

4.3. Increase in fixed, fully enclosed designs

The surge in group 2 designs aligns with the rise of AM, which enables prefabricated, patient-specific solutions that reduce application time. Since 2017, AM has been used as a fabrication technique for prefabricated patented immobilization designs, offering solutions for efficiency and customization. The temporal distribution of the analyzed patented fracture immobilization designs reveals a notable surge in those classified as fixed and fully enclosed, group 2 (Figure 5). This observed trend aligns with the arrival of AM, a contemporary production technique, facilitating prefabrication. These prefabricated, ready-to-use designs decouple fabrication and application reducing application time for both patient and clinician. While patents such as those by Sethuraman [29] and Muñoz [34] provide detailed fabrication methods, they do not address integration into hospital workflows. Although AM allows for prefabricated tailor-made immobilization designs 3D-printing technologies have not become the primary mean in the fabrication of orthopedic cast [90]. This finding illustrates both the technological potential of AM and the gap between the design of innovative patented immobilization solutions and their clinical implementation.

In conclusion, this study demonstrates the persistent design drivers of patents and the emerging technological influences in designing solutions for fracture immobilization. The monitoring of patent activity can serve as an early indicator of emerging trends in immobilization technology. However this analysis is limited to patents and does not evaluate the clinical performance of the devices described. Further interdisciplinary collaboration between clinicians, engineers, and industry stakeholders is recommended to accelerate translation from patent to practice. While innovative prefabricated designs are emerging, conventional plaster remains dominant in many contexts due to cost and accessibility [6]. Future research should examine how patented innovations can align with clinical protocols and real-world practice, particularly regarding workflow integration and cost-effectiveness.

5. Conclusion

This study examined the evolution of patented immobilization designs for fractures of human extremities, revealing how technological innovation and enduring clinical needs have shaped their development. Across decades of patent activity, air circulation has remained a persistent design priority, reflecting the ongoing clinical concern for skin health and patient comfort noted in earlier orthotic research. Adjustable designs dominated the analyzed patents, supporting prior evidence that adaptability is essential in fracture management, both for accommodating swelling and for improving comfort. More recently, the surge in fixed and fully enclosed designs coincides with the rise of additive manufacturing, a technology that offers precision and prefabrication advantages.

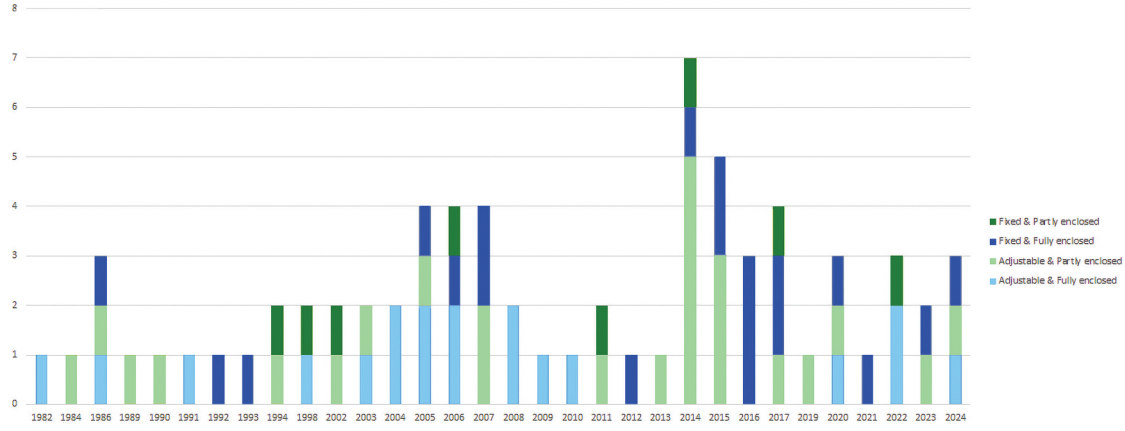


Figure 5. Temporal distribution of patented immobilization designs based on their design classification.

However, in line with previous literature, this study also highlights a clear implementation gap: despite the availability of innovative prefabricated designs, plaster casting remains the most common solution in daily practice due to cost and availability [6]. These findings demonstrate that while patents capture both persistent clinical requirements and the promise of new fabrication methods, translation into clinical practice remains limited. This study demonstrates in using patent analysis to map long-term design trajectories, the gap between industry innovation and clinical adoption. This underscores the need for future work on integrating patented technologies into hospital workflows and evaluating their clinical and economic feasibility.

6. Expert opinion

6.1. Real-world impact and barriers to adoption

Fracture immobilization will remain a cornerstone of trauma care, but current methods – plaster and synthetic casts – are associated with complications such as skin problems, joint stiffness, and patient discomfort [6]. Recent advances in 3D scanning and additive manufacturing hold promise for improved personalization, patient comfort, and integration of monitoring features. However, clinical adoption is limited by long production times, misalignment with hospital logistics, and inconsistent scanning accuracy. The 26-hour turnaround for 3D-printed devices [91] cannot currently compete with the 45-minute application of fiberglass casts [92]. Furthermore, stricter European MDR regulations increase the resources and time required for market entry, further slowing adoption.

6.2. Key areas for improvement and limitations

Critical barriers include the accuracy and resolution of current scanning methods, which may distort limb geometry and compromise fit. The practice of mirroring the contralateral limb introduces additional risks, as asymmetry in forearm musculature and bone morphology can lead to poor alignment [92]. Usability issues are also evident: although many patented devices claim adjustability, few specify standardized adjustment protocols or clarify patient versus clinician responsibilities. Technological advances must therefore be complemented by clear clinical guidelines and workflow integration.

6.3. Research potential and endpoints

Further research is recommended into smart immobilization technologies that incorporate sensing and stimulation, enabling real-time monitoring of healing and potentially mitigating complications such as muscle atrophy. Modular prefabrication strategies represent another promising design path, balancing efficiency and personalization while reducing environmental impact through reuse [93]. Controlled functional dynamization – allowing limited, guided motion at the fracture site – also merits study, given evidence that early mobilization may accelerate healing [94]. However, the field currently lacks robust clinical trials to establish safety, cost-effectiveness, and definitive endpoints.

6.4. Future directions in the field

Fracture immobilization will remain a central clinical priority, but progress is most likely to come from hybrid approaches rather than fully bespoke designs. Prefabricated, modular solutions that integrate limited customization are more realistic for hospital workflows than purely patient-specific 3D-printed devices. While innovations in sensing and dynamization may redefine standards of care, these advances must be balanced with regulatory and economic realities. Other areas in trauma care – such as biologics for accelerated bone healing – are being explored, but immobilization itself is unlikely to be replaced in the foreseeable future.

6.5. Outlook for the next 5–10 years

In the coming decade, immobilization devices may evolve into hybrid systems combining prefabrication, digital customization, and sensor-based monitoring. Such devices could offer superior comfort, improved clinical outcomes, and reduced complication rates compared to conventional casts. Yet these gains may come with trade-offs: higher costs, more complex regulatory pathways, and the need for new clinical workflows. Ultimately, success will depend on whether technological innovation can be translated into clinically feasible, cost-effective solutions that meet regulatory standards.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Declaration of interests

The authors have no relevant affiliations or financial involvement with any organization or entity with a financial interest in or financial conflict with the subject matter or materials discussed in the manuscript. This includes employment, consultancies, honoraria, stock ownership or options, expert testimony, grants or patents received or pending, or royalties.

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Appendix A: Overview of the patented designs indicating their design group, application, adjustability if applicable and fabrication

Patent Name	Design group	Inventor(s)	Application	Solutions Adjustability	Fabrication
Conformable Brace	Fixed & Partly Enclosed (group 1)	Allenberg Kurt, Scholz Matthew T, Edgar Jason L	Upper & Lower Extremity	NA	Prefabricated
Cast Assembly With Breathable Double Knit Type Padding		Grim Tracy E, Iglesia Joseph M, Henderson Wendy, Long Kelly M, Campos Michael, Doubleday Walter	Upper & Lower Extremity		Customized During Application
Splint		King Richard	Upper & Lower Extremity		Prefabricated
Wrist Brace		Krajewski Stephan, Hass Oliver, Van Den Berg Emma, Gengler Daphne	Finger, Hand Or Wrist		Prefabricated
Splint Device		Nsubuga Martin	Pediatric Femoral		Prefabricated
Curable Adhesive Splints And Methods		Singh Balbir, Pek Lim Fang, Allenberg Kurt	Upper & Lower Extremity		Prefabricated
Splint		Starkey Paul, Ozturkatalay Okan	Finger, Hand Or Wrist		Prefabricated
Spiral Brace		Summit Scott. Trauner Kenneth B	Upper & Lower Extremity		Prefabricated
Production Of A Custom Medical Splint Or Brace For Immobilization Of A Selected Region Of A Patient's Body Part		Schuind Frédéric	Upper & Lower Extremity		Prefabricated
Orthopedic Cast System And Method	Fixed & Fully Enclosed (group 2)	Campagna Anthony J, Scholz Matthew T	Upper & Lower Extremity	NA	Customized During Application
A Breathable And Customized Cast For Immobilization Of Fractured Limb		Chhatrala Pankaj Kumar K, Jamdade Nikhil Kailas, Saksena Devanshi, Garg Bhavuk	Upper & Lower Extremity		Prefabricated
Splint Using Thermoplastic Resin Fabric And Manufacturing Method Therefor		Eum Jang Hwan	Upper & Lower Extremity		Prefabricated
Soft Cast Material		Evans John C	Upper & Lower Extremity		Customized During Application
Orthopedic Splint		Evans John C, Chabba Shitij, O'hara Martin	Upper & Lower Extremity		Customized During Application
Curable Immobilizing Cast Dressing		Grabowski Rafal, Kroczek Beata, Kurzep Piotr, Kupaj Szymon	Upper & Lower Extremity		Prefabricated

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Patent Name	Design group	Inventor(s)	Application	Solutions Adjustability	Fabrication
Orthopedic Cast System		Honeycutt Travis W, Setzer Barry D	Upper & Lower Extremity		Customized During Application
A Method For Producing A Brace, The Brace As Such, And A Method To Fix The Position Of A Broken Bone In A Limb		Janzing Heinrich Mark Jan	Upper & Lower Extremity		
Moldable Injury Therapy Device And Method		Jorissen Koen Jozef Maria	Upper & Lower Extremity		Customized During Application
Kit And Method For Making A Splint		Liddle Katherine, Murdock Michael, Medina William	Upper & Lower Extremity		Customized During Application
Methods For Fabricating Immobilization Apparatus		Muñoz Javier, Climent Toni, Monzon Luis, Pedrajas Lucas. Monzon Juan	Upper & Lower Extremity		Prefabricated
Improved Orthopedic Splinting Article		Nelson Thomas W	Upper & Lower Extremity		Customized During Application
Thermoplastic Cast With Excellent Transformability And Rigidity.		Park Jongchil	Upper & Lower Extremity		Prefabricated
3d-Printed Splint For Immobilising Limbs Or The Pelvis		Peters Syllm Stephan	Upper & Lower Extremity		Tailor Made
Clavicle Fracture Infant Brace		Quist Kirsten	Pediatric Clavicula		Prefabricated
Improved Casting And Splinting Product Having Multiple Plaster Setting Rates		Schulz George A	Upper & Lower Extremity		Customized During Application
Fabrication Of 3d-Printed Fracture-Specific Orthopaedic Cast		Sethuraman Swaminathan, Subramanian Anuradha, Kannan Vishal	Upper & Lower Extremity		Tailor Made
Splint For The Setting And Immobilisation Of The Limbs		Tadic Smilja	Upper & Lower Extremity		Prefabricated
Multi-Layer Cast Systems And Methods		Wu Benjamin M, Reed Stephanie, Wang Jeffrey C, Loughran Emily W	Upper & Lower Extremity		Customized During Application
Fracture First-Aid Fixator	Adjustable & Partly Enclosed (group 3)	Bai Xueling, Zhang Peng	Upper & Lower Extremity	Adjustable Fit	Prefabricated
Orthopedic Walking Brace Having A Curved Sole		Batterson Benjamin, Sasidharan Manikandan, Loughnane Christopher P, Hugger Derek, Panecki Lee, Aiston Chris	Lower Extremity	Adjustable Fit	Prefabricated
Hand Finger Narthex		Bogris Nektarios	Finger, Hand Or Wrist	Adjustable Fit	Prefabricated
Spherical Section Hand Splint		Brown Charles L	Finger, Hand Or Wrist	Adjustable Fit	Prefabricated

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Patent Name	Design group	Inventor(s)	Application	Solutions Adjustability	Fabrication
Wrist Brace		Daneman Alexis G	Finger, Hand Or Wrist	Adjustable Fit	Prefabricated
Functional Cast Therapy Product And Method		Darcey Thomas D	Upper & Lower Extremity	Adjustable Fit	Prefabricated
Orthopedic Appliance For Use In Treating Fractured Clavicles		Florek Florian F	Clavicula	Adjustable Fit & Position	Prefabricated
Splint For Immobilizations In The Area Of The Hand		Forstner Wolfgang, Foller Guenther	Finger, Hand Or Wrist	Adjustable Fit	Prefabricated
Brace For Correction Of Humeral Fractures		Grant Gregory, Schillig Jeremiah	Humerus	Adjustable Fit & Position	Prefabricated
A Soft-Goods Type, Formable Orthopedic Cast		Grim Tracy E	Upper & Lower Extremity		Prefabricated
Adjustable Wrist And Hand Splint		Grim Tracy E, Gamble Fritz F	Finger, Hand Or Wrist	Adjustable Fit	Prefabricated
Curable Splint For Orthopedic Use		Huh Tae-Hee	Upper & Lower Extremity	Adjustable Fit	Prefabricated
Ambidextrous Wrist Brace With Thume Immobilizer		Jaccard Jean-Patrick	Finger, Hand Or Wrist	Adjustable Fit & Position	Prefabricated
Splint Combined Use Cast Absence For Bone Fracture Fixing		Kim Kyung-Jin	Upper & Lower Extremity	Adjustable Fit	Prefabricated
A Splint		Kumar Kumar	Upper & Lower Extremity	Adjustable Fit & Position & Some Freedom Of Movement	Prefabricated
Orthopedic Shoulder Device		Lemmon Damon Romito, Myers Thomas Howard, Garten Ii Charles Edward, Taylor Scott Andrew	Shoulder	Adjustable Fit & Position	Prefabricated
Method And System Of Designing A Customised Splint For A Body Part		Lotfi Reza, Nakhaee Farzaneh, Komari Alaei Hannan, Moradi Ali, Nia Mohammad Mahdi Ghaemi	Finger, Hand Or Wrist	Adjustable Fit	Tailor Made Prefabricated
Brace For Reducing And Stabilizing Fracture In Human Hand		Macarthur Robert	Finger, Hand Or Wrist	Adjustable Fit	Prefabricated
Support Device		Macfarlane Doniert	Finger, Hand Or Wrist	Adjustable Fit	Prefabricated
Walking Brace		Pick Erez	Lower Extremity	Adjustable Fit	Prefabricated
Thumb Brace		Roussel Anaïs, Sagardia Beñat	Finger, Hand Or Wrist	Adjustable Fit	Prefabricated
Brace For Supporting A Limb Of A Patient		Summit Scott, Trauner Kenneth B	Upper & Lower Extremity	Adjustable Fit	Prefabricated
Splint		Torrens George Edward	Upper & Lower Extremity	Adjustable Fit & Position	Prefabricated
Brace For Immobilising A Traumatized Or Operated Shoulder		Turconi Francesco, Rossi Paolo	Shoulder	Adjustable Fit & Position	Prefabricated
Method And Brace To Immobilize Fractures		Viegas Steven F, Tencer Allan F, Woodard Peggy L, Gaynor Sue J	Finger, Hand Or Wrist	Adjustable Fit	Prefabricated
Improved Modified Orthotic Device	Adjustable & Fully Enclosed (group 4)	Anderson George Clarence	Finger, Hand Or Wrist	Adjustable Fit & Position	Prefabricated

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Patent Name	Design group	Inventor(s)	Application	Solutions Adjustability	Fabrication
An Orthopedic Scaffold Device For Fixing Bone Fracture		Badhe Ravindra Vijay, Badhe Sonali Ravindra	Upper & Lower Extremity	Adjustable Fit	Prefabricated
Surgical Cast Venting Device And Material		Barberio Alessandro	Upper & Lower Extremity	Adjustable Fit & Position	Prefabricated
Adjustable Immobilizing Joint Brace		Cheng Gene C, Ness Arnold R	Upper & Lower Extremity	Adjustable Fit & Position	Prefabricated
A Segmented All-Fit Adjustable Fracture Cast For Treating Bone Fractures		Dharmalingam Ponnuswamy Kathiresan, Muthukumaraswamy Rabakavi Naveen, Tarachandra Swetha, Muthukumaraswamy Srilekha	Upper & Lower Extremity	Adjustable Fit & Position	Prefabricated
Orthotic Device, Orthotic System And Methods Of Manufacture And Use Thereof		Geremtzes Charalampos, Moustakas Dimitrios	Upper & Lower Extremity	Adjustable Fit	Prefabricated
Versatile Hardenable Cast Or Support		Grim Tracy E, Henderson Wendy J, Long Kelly M, Iglesias Joseph M, Campos Michael	Upper & Lower Extremity	Adjustable Fit	Prefabricated
Fracture Brace		Hargrave David C, Prais Eugene	Upper & Lower Extremity	Adjustable Fit	Prefabricated
Replaceable Rigid Cast With Integral Fasteners		Hill-Byrne Christopher R	Upper & Lower Extremity	Adjustable Fit	Prefabricated
Orthopedic System For Immobilizing And Supporting Body Parts		Joseph Mark	Upper & Lower Extremity	Adjustable Fit	Prefabricated
Vacuum Splint Device		Liesmann Richard C, Daugherty David A	Upper & Lower Extremity	Adjustable Fit	Prefabricated
Semi-Rigid Compression Splint For Application Of Three-Dimensional Force		Manoach Seth M, Strauss Elton	Upper & Lower Extremity	Adjustable Fit	Prefabricated
Flexible Ribbed Splint System		Narula Vinod K, Narula Dipak	Upper & Lower Extremity	Adjustable Fit	Prefabricated
Immobilizing Wrist Brace		Nelson Ronald E, Bjornson Karl E	Finger, Hand Or Wrist	Adjustable Fit	Prefabricated
Fixator Or Splint		Pomeroy Linda, Bajwa Ali	Upper & Lower Extremity	Adjustable Fit & Position	Prefabricated
Negative Pressure Therapy System For Heat-Moldable Splint		Rehbein Jonathan G, Randolph Larry Tab, Ausen Ronald W, Scholz Matthew T	Upper & Lower Extremity	Adjustable Fit	Prefabricated
Immobilizing And Supporting Inflatable Splint Apparatus		Reis Daniel, Zucker Dalia, Bin Nun Asher	Upper & Lower Extremity	Adjustable Fit	Prefabricated
Brace For Fixation Of Bone Fractures		Thibodaux Peggy L	Upper & Lower Extremity	Adjustable Fit	Prefabricated