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DESIGN FOR ADDITIVE MANUFACTURING CONSIDERATIONS FOR COMPLIANT CONSTANT-FORCE MECHANISMS

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Abstract

Compliant Mechanisms are a class of mechanisms that utilize bending to achieve motion. Compliant Constant-Force Mechanisms (CCFMs), a unique subset of compliant mechanisms, can deliver a constant force output over a fixed range of motion; these mechanisms are often planar systems driven by traditional manufacturing design principles and can be generated using a variety of methods. Some methods, such as rigid body replacement, are constrained to pins and linkages whereas those generated with topology optimization may possess more organic shapes. Traditional methods of manufacturing drive a wide variety of these designs. Applying principles dictated by Design for Additive Manufacturing (DfAM) may yield better designs for these complex applications. This paper identifies clear, concise themes that elucidate ways to leverage Additive Manufacturing for CCFMs using examples from existing literature. These identified themes fall within (1) the use of geometric complexity, (2) material considerations, especially between polymers and metals, and (3) the breadth of applications of current CCFMs.

Keywords: Additive Manufacturing, Compliant Mechanisms, Constant Force Mechanisms, Design for Additive Manufacturing

Abbreviations:

CM – Compliant Mechanism
CFM – Constant Force Mechanism
CCFM – Compliant Constant-Force Mechanism
SCCFM – Stiffness Combine CFM
CBCFM – Curved Beam CFM
SOCFM – Shape Optimized CFM
CrSCFM – Cross Spring CFM
CFCM – Constant Force Compression Mechanism
GMSM – Generalized Multiple Shooting Method
AM – Additive Manufacturing
DfAM – Design for Additive Manufacturing
EDM – Electrical Discharge Machining
SMA – Shape Memory Alloy
PLA – Polylactic Acid
TPU – Thermoplastic Polyurethane
TPE – Thermoplastic Elastomer
POM – Polyoxymethylene
PEEK – Polyether Ether Ketone
MEX – Material Extrusion
MJT – Material Jetting
VPP – Vat Photopolymerization
PBF – Powder Bed Fusion
DED – Directed Energy Deposition
FEA – Finite Element Analysis

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1. Introduction

Compliant Mechanisms transfer force, energy, and motion through the bending of flexible elements of different shapes and sizes. They have been used in various areas of engineering, especially for applications involving precision motion such as biomedical devices [1–3], robotic devices [4–6], or aerospace applications [7–9]. Compliant mechanisms help to address some of the challenges with traditional mechanisms, which often consist of multiple moving parts and mechanical assemblies, the presence of which makes these traditional mechanical devices undesirable. This is due to increased production costs, increased assembly time, and more points of failure. Constant Force Compliant Mechanisms (CCFMs) are a special category of compliant mechanisms that can apply a near-constant force over a predefined displacement range. This characteristic makes constant force mechanisms highly sought after because they eliminate the need for sensor-controller systems and the complex algorithm required to operate a given system, not to mention the expensive equipment and the high computational cost. As an alternative to traditional constant-force mechanisms, CCFMs have significant benefits given the use of passive force control, low cost, and ease of use.

While compliant mechanisms and CCFMs can benefit a range of applications, they have been gaining traction in the medical field, especially in medical tools and devices that require extreme precision and the ability to be functional in minimal space. As an example, Huxman et al. have shown that compliant mechanisms have been used in orthopedic implants [10], while Thomas et al. demonstrated the use of compliant mechanisms in multiple areas in the field of surgery [11]. In the case of constant force mechanisms, a CCFM was designed for inner ear inspection by Tissot-Daugette et al. [12]. This device prevents accidental overload beyond 1 gram-force (gf). However, when contrasted against traditional mechanisms, compliant mechanisms require higher levels of control over manufacturing capabilities given their reliance on bending for motion. This is especially pertinent in the medical field, where performance demands on compliant mechanisms and CCFMs are high. Because of this, there is significant potential in exploring the use of additive manufacturing (AM) in advancing the design and realization of compliant mechanisms.

The design and manufacture of medical devices require higher precision, precise tolerances, and above all reliability and safety. Manufacturing of medical devices such as implants [13], prosthetics and orthotics [14], exoskeletal braces [15], and surgical devices [16] are being researched, all leveraging AM to meet the robust demands of the medical field. AM models have also been used for training surgeons in practice and reducing the risk of mortality by allowing surgeons to visualize and plan better [17]. Commonly used AM processes in medical device manufacturing are MEX, VPP, MJT, and PBF [11,18]. There is a wide list of requirements when it comes to the selection of AM materials in medical devices depending on the area of use. The literature identifies biocompatibility, strength, stiffness, elasticity, durability, transparency, sterilizability, and chemical resistance as desirable material properties for the design of medical devices [11,15,19]. From a manufacturing perspective, AM is an ideal candidate for these parts. Low-cost solutions such as those produced via Material Extrusion (MEX) can allow for rapid iteration of design solutions directly on-site. Polymers such as PLA are being tested for implants by plating them with metals [20]. Additionally, using high-strength AM materials like carbon fiber-reinforced plastics and metals may further enhance desirable properties. Within the medical field, AM enables the design and cost-efficient creation of personalized medical solutions through mass customization, including implants and prosthetics [21,22]. Finally, the geometric complexity enabled by AM can potentially result in medical solutions that are lightweight and better performing than bulkier, conventional solutions [23].

The advantages afforded by CCFMs would be a valuable addition to the field of medical devices because of their unique functional attributes. Traditionally, CCFMs have been manufactured using subtractive manufacturing. Applying the design opportunity enabled by AM to these mechanisms could provide CCFM designers with more control, especially considering the seemingly unlimited geometric complexity achievable with AM. This paper aims to increase the use of additively manufactured CCFMs in medical devices by examining existing CCFMs through the lens of geometric complexity, material complexity, and application areas. By conducting this survey, designers will not only better understand how AM impacts CCFM design within the medical device field but will also be able to identify avenues for future expansion of this unique mechanism design approach.

2. Theoretical Background

This section offers a background into the standard practices and modeling techniques used to design CCFMs. This section will also discuss the state of the art in manufacturing compliant mechanisms using AM.

2.1. Categorizing and Modeling Compliant Constant-Force Mechanisms (CCFMs)

This subsection presents the various modeling methods and tools available for designing CCFMs. These methods are intended to satisfy the functional requirements by using principles of kinetostatic modeling to obtain the desired force and displacement within the constraints of the application [24]. The design process begins by identifying the application and the constraints of the desired application. The synthesis method chosen dictates the next step of the design process. For instance, in a stiffness combine constant force mechanism, positive stiffness and negative stiffness elements are employed in parallel to obtain a quasi-zero stiffness zone where the force plateaus and a constant force region is obtained [25]. The process requires identifying a positive stiffness element like a straight beam and a negative stiffness element like a tilted, curved, or arched beam [26] to be used together. Wang and Xu [27] have performed a systematic review of the various constant force mechanisms along with the pros and cons of each type of mechanism. According to Wang and Xu, Compliant Constant-Force Mechanisms (CCFMs) primarily have five categories as listed below:

- Stiffness Combine Constant Force Mechanism (SCCFM) - These devices work by combining positive and negative stiffness flexures to achieve a zero-stiffness device [25]. An SCCFM entails a minimum of two thin leaf flexures (negative and positive stiffness) usually arranged in a pattern to obtain the desired characteristics.
- Curved Beam Constant Force Mechanism (CBCFM) - These devices, as the name suggests, work on the principle of using the properties of a curved beam to achieve zero stiffness by virtue of its curved shape [28]. A CBCFM will have curved surfaces, an advantage of which is that the shape induces buckling [29], which creates a zero stiffness resultant.

- Shape Optimized Constant Force Mechanism (SOCFM) - This category of mechanisms uses similar principles to that of CBCFMs however instead of having curved beams these beams have a more complex shape [30]. A SOCFM is in line with a topology-optimized design, meaning the result will be an organic geometry.
- Cross Spring Constant Force Mechanism (CrSCFM) - These devices have zero stiffness attributed to the arrangement of flexures to provide pin joint-like properties [31]. A CrSCFM uses multiple small flexures arranged in a specific way to get the zero-stiffness characteristic.
- Constant Force Compression Mechanism (CFCM) - These devices are based on the configurations of the pseudo-rigid body model of a slider crank mechanism [32]. A CFCM has rigid segments and flexible segments that will allow the mechanism to attain the zero-stiffness characteristic.

These categorization methods and their working principles are important for designers to consider the type of structural elements that will appear in their design. Each category provides a unique shape. The math required to obtain the sizes of these CCFMs is obtained from existing design tools. Wang and Xu [27] and Ling et al. [24] both discussed the following design tools for the synthesis of Compliant Constant-Force Mechanisms.

- Pseudo Rigid Body Modeling
- Elliptic Integral Method
- Generalized Multiple Shooting Method
- Chain Beam Algorithm
- Finite Element Method
- Topology Optimization

These tools are commonly employed in the designing of CCFMs. Certain methods have advantages over others. Using elliptic integrals will give you a very accurate result, however, they are computationally heavy and time-consuming. The pseudo rigid body method is relatively easier however, it is only accurate up to 99.5% of the elliptic integrals solution for an end angle of less than 77 degrees [33]. Most if not all designs generated are verified by using an analysis method like Finite Element Analysis. This goes to say that each design tool has certain advantages and disadvantages that must be considered.

2.2. Intersection of Additive Manufacturing and Compliant Mechanisms

Compliant mechanisms are typically manufactured using a range of both additive manufacturing and subtractive manufacturing. However, the focus of this paper is realizing CCFMs with additive methods. As such, it is important to understand existing state-of-the-art approaches to compliant mechanisms that are manufactured using AM. For example, Lateş et al. [34] have compared the fabrication process of compliant mechanisms using three different manufacturing methods with three different materials. The authors recommend using Additive Manufacturing (AM) for complex designs and small parts. Similarly, Wang et al. [35] conducted a review of manufacturing methods of compliant micro mechanisms. In their work, they presented a detailed analysis of eight manufacturing methods used for compliant micromechanisms and showed that biocompatible polymers are preferred in biotechnology, bionics, and robotics-related applications.

As further examples of compliant mechanism designs produced via AM, Chandrasekaran and Thondiyath [36] designed a compliant surgical tool tip and printed it using MJT. The mechanism has circular guides on the edges along with a central tether cut out in a cylindrical cross-section arranged in an alternate fashion that enables two degrees of freedom. Barros et al. have created an origami hand orthosis manufactured using MJT [37]. Their study uses a multi-material approach with rigid and flexible materials to form a Yoshimura origami pattern where the fold of the pattern uses flexible material to bend and can be personalized to an individual's specifications. Bosclair et al. have used rolling contact joints in a prosthetic hand model [38]. The examples mentioned above, the surgical tooltip, the origami hand orthosis, and the prosthetic hand model demonstrate how AM can be used to create personalized highly complex, functional, compliant mechanism designs with multiple materials in a single print that can be personalized at a relatively low cost.

Broadly speaking, the near-unlimited design freedom offered by AM in the form of geometric complexity, material complexity, and functional complexity has benefited compliant mechanisms. However, there is still a need to understand how such complexity can and should be exploited to expand the horizons of the design of CCFMs, given their unique functional characteristics when compared with traditional compliant mechanisms. In this paper, we explore the bounds of some of these AM principles by using CCFM examples from the current literature to help identify such emergent opportunities.

3. Survey and Synthesis of Compliant Constant-Force Mechanisms Suitable for Additive Manufacturing in Medical Devices

In this section, we show a summary version of mechanisms gathered from the literature. These have been broken into two categories, (1) general CCFMs and (2) medical application CCFMs. This is done to draw attention to the smaller number of medical applications CCFMs despite the highly desirable characteristics of these mechanisms discussed in Section 1.

3.1. Scope of CCFM Search and Identification Strategy

For this paper, mechanisms are identified from relevant literature in the CCFM space. Various examples from precision manipulation systems, robotic grippers, overload protection systems, and medical application systems are included. One of the major criteria for initial screening and selection was the presence of a final manufactured artifact. This is important to this survey because the absence of a manufactured part makes it difficult to gauge manufacturability parameters, such as how well the design adheres to typical DfAM restrictions. Mechanisms manufactured using both additive and subtractive manufacturing methods have been included. This is to identify potential pathways to convert traditionally subtractive manufacturing-oriented designs to AM.

3.2. Collected Cross-Section of CCFM Designs in Literature

Table 1 shows the list of collected compliant constant-force mechanisms. The theoretical and experimental values for the force and displacement are noted; these values will help designers understand the capacity at which these mechanisms perform. The theoretical value is defined as either an analytical or a simulation-based value. These values are noted to see if there is a significant difference between the analytically calculated value and the experimental results.

Along with this, information regarding the manufacturing method and material used are also recorded in Table 1 to understand the type of materials that are predominantly used in the manufacture of CCFMs and if certain synthesis methods frequently correspond to specific manufacturing methods or materials.

Table 1. Examples of Compliant Constant-Force Mechanisms

Author	Mechanism Type	Force	Displacement	Method Used	Manufacturing Method	Material
Liu et al. [39]	SCCFM	0.62 N [Theoretical]; 0.53 N [Experimental]	0.246 mm [Theoretical]; 0.22 mm [Experimental]	Elliptic Integrals, FEA	Subtractive [Wire EDM]	Metal [Al-6061]
Liu and Xu [40]	SCCFM	1.3 N [Theoretical]; 1.1 N [Experimental]	0.216 mm [Theoretical]; 0.2 mm [Experimental]	Elliptic Integrals, FEA	Not Specified	Not Specified
Liu and Xu [41]	SCCFM	28 N [Theoretical];	1 mm [Theoretical]; 0.186 mm [Experimental]	FEA	Not Specified	Metal [Al-70754]
Hao et al. [42]	SCCFM	5.31 N [Theoretical]; 7.11 N [Experimental]	>3 mm	NA	Subtractive [CNC Mill]	Polymer [Polycarbonate Sheets]
Xu [43]	SCCFM	29.1 N [Theoretical]; 12.6 N, 30.1 N [Experimental]	4.44 mm [Theoretical]; 1.78 mm [Experimental]	Elliptic Integrals, FEA	Subtractive [Wire EDM]	Metal [Al-7075]
Wang and Xu [44]	SCCFM	32 N [Theoretical]; 29 N [Experimental]	0.8 mm [Theoretical]; 0.7 mm [Experimental]	Elliptic Integrals, FEA	Subtractive [Wire EDM]	Metal [Al-7075]
Wang and Lan [45]	CBCFM	20.383 N, 40.766 N [Theoretical]; 23.517 N, 46.379 N [Experimental]	2.578 mm	GMSM	Not specified	Polymer [PEEK]
Pham and Wang [28]	CBCFM	11 N	7 mm	GMSM	Subtractive [Milling]	Polymer [Polyoxymethylene (POM)]
Chen and Lan [30]	SOCFM	5 N	4 mm	GMSM	Not Specified	Polymer [POM]
Weight et al. [46]	SOCFM	4.39 N [Theoretical]; 9.47 [Experimental]	0.6 mm	Topology Optimization	Not Specified	Metal [Not Specified]
Tolman et al. [47]	SCCFM	1 N	>30 mm	PRBM	Additive [Not Specified]	Polymer [PLA]
Morsch and Herder [31]	CrSCFM	NA	NA	NA	Subtractive [Not Specified]	Metal [Spring Steel]
Liu et al. [48]	SOCFM	9.6 N [Experimental]	3 mm [Experimental]	Topology Optimization	Additive [MEX]	Polymer [TPE]
Xu et al. [49]	SCCFM	2.692N [Theoretical]; 2.633 N [Experimental]	1.389 mm [Analytical]; 0.886 mm [Experimental]	PRBM	Additive [Not Specified] with SMA alloy wire	Not Specified
Tong et al. [50]	SCCFM	1.90 N [Theoretical]; 2.20 N [Experimental]	1.5 mm [Analytical]; 1.570 mm [Experimental]	Topology Optimization, FEA	Additive [MEX]	Polymer [ABS]
Wang et al. [51]	NA	2.6 N	27 mm	Chained Beam Algorithm	Subtractive [Laser Cutting]	Metal [Steel]
Qin et al. [52]	SCCFM	45.5 N	1 mm	PRBM, FEA	Subtractive [Wire EDM]	Metal [Al-7075]
Wang et al. [53]	CBCFM	1.5 N [Theoretical]; 1.64 N [Experimental]	12 mm [Theoretical and Experimental]	GMSM	Subtractive [Wire Electrode Cutting]	Metal [Ti-55.82at%Ni SMA]
Liu et al. [54]	SOCFM	41.9 N [Experimental]	15 mm [Experimental]	Topology Optimization, FEA	Additive [MEX]	Polymer [TPE]

From the collected cross-section of designs, we notice that several designs could undergo simple modifications that would make them better for AM. Out of the nineteen mechanisms in Table 1, nine have been manufactured using subtractive manufacturing, five have been manufactured using AM, and five have not explicitly stated their manufacturing method. Nine of the mechanisms use a metal as a material, eight use a polymer, and two have not explicitly stated the material used. Figure 1 shows a picture of each manufactured artifact for the CCFMs listed in Table 1. This shows the different designs and topologies that the categorization methods in Section 2.1 may generate.

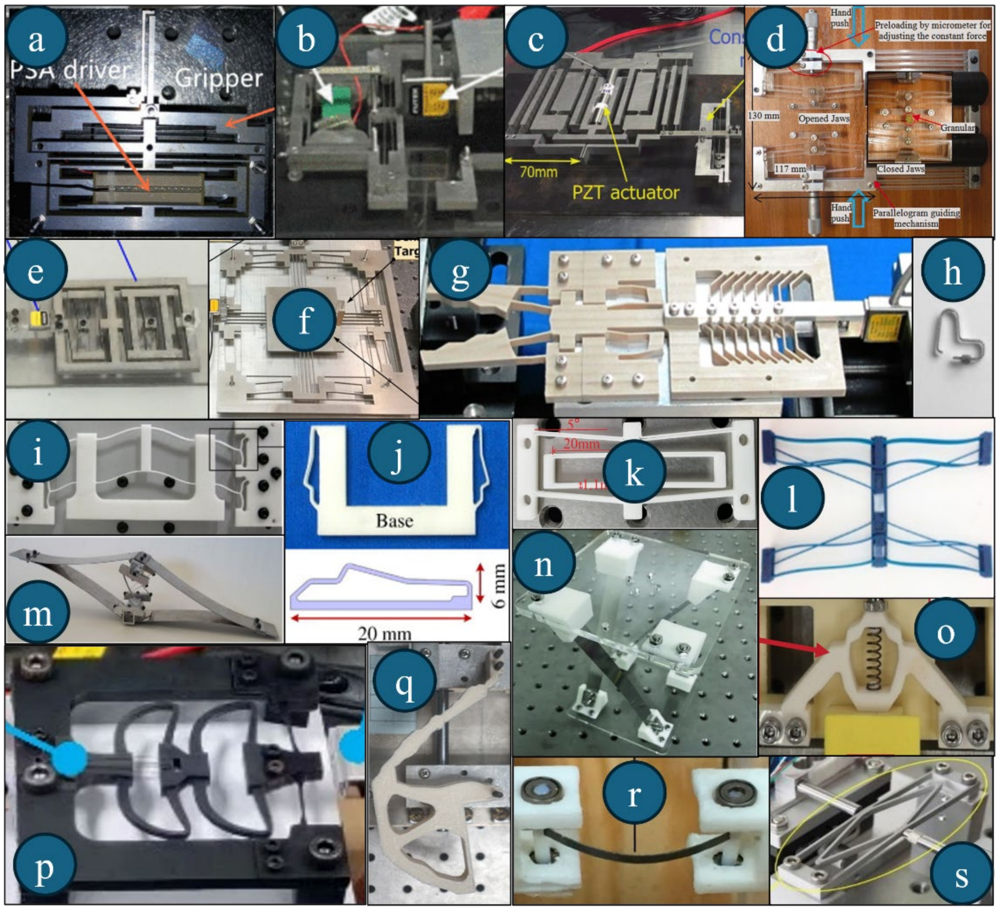

Figure 1. CCFMs Identified from Literature (a.) Liu et al. *[39]* (b.) Liu and Xu *[40]* (c.) Liu and Xu *[41]* (d.) Hao et al. *[42]* (e.) Xu *[43]* (f.) Wang and Xu *[44]* (g.) Wang and Lan *[45]* (h.) Weight et al. *[46]* (i.) Pham and Wang *[28]* (j.) Chen and Lan *[30]* (k.) Tong et al. *[50]* (l.) Tolman et al. *[47]* (m.) Morsch and Herder *[31]* (n.) Wang et al. *[51]* (o.) Liu et al. *[48]* (p.) Xu et al. *[49]* (q.) Liu et al. *[54]* (r.) Wang et al. *[53]* (s.) Qin et al. *[52]*

Table 2 overs a more condensed view of CCFMs from literature. Specifically, it shows Constant Force Mechanisms tailored to medical applications. This includes surgical tools, surgical robots, and other assistive medical devices. Note that there are fewer mechanisms represented in this table when compared with Table 1; this can potentially be attributed to the stringent design, manufacturing, and material requirements for biomedical applications.

Table 2. Compliant Constant-Force Mechanisms used for Surgical, Robotic, and other medical applications

Author	Mechanism Type	Force	Displacement	Method Used	Manufacturing Method	Material
van de Sande et al. [55]	NA	.078 N [Theoretical]; 0.13 N [Experimental]	20 mm [Theoretical]; 35 mm [Experimental]	FEA	Subtractive [Not Specified]	Metal [Stainless Steel]
Tissot-Daguette et al. [12]	CrSCFM	0.0098 N [Theoretical and Experimental]	0.87 mm [Theoretical and Experimental]	Elliptic Integral, FEA	Additive [Femtolaser AM (DED)]	Polymer [Fused Silica (Glass)]
Sun and Leuth [56]	CrSCFM	6 N	11 mm	PRBM, FEA	Additive [SLS]	Polymer [Polyamide (PA2200)]
Cheng et al. [57]	SOCFM	4, 5, 6 N [Theoretical]; 3.9, 5, 6.1 N [Experimental]	10 mm [Theoretical and Experimental]	Topology Optimization, FEA	Not Specified	Polymer [PLA]
Cheng et al. [58]	SOCFM	0.55 N [Theoretical]; 0.4 N [Experimental]	25 mm [Theoretical]; 20 mm [Experimental]	Topology Optimization, FEA	Additive [Not Specified]	Polymer [PLA]

At first glance, there appear to be several similarities within the collected designs between Table 1 and Table 2. However, out of the five mechanisms identified in Table 2, three mechanisms have been manufactured using additive techniques, one using subtractive, and one has not explicitly stated the manufacturing method. This is much higher than the number of mechanisms that have used AM in Table 1. From Table 2, one mechanism uses a metal, while the others use a polymer. Figure 2 shows the manufactured artifacts.

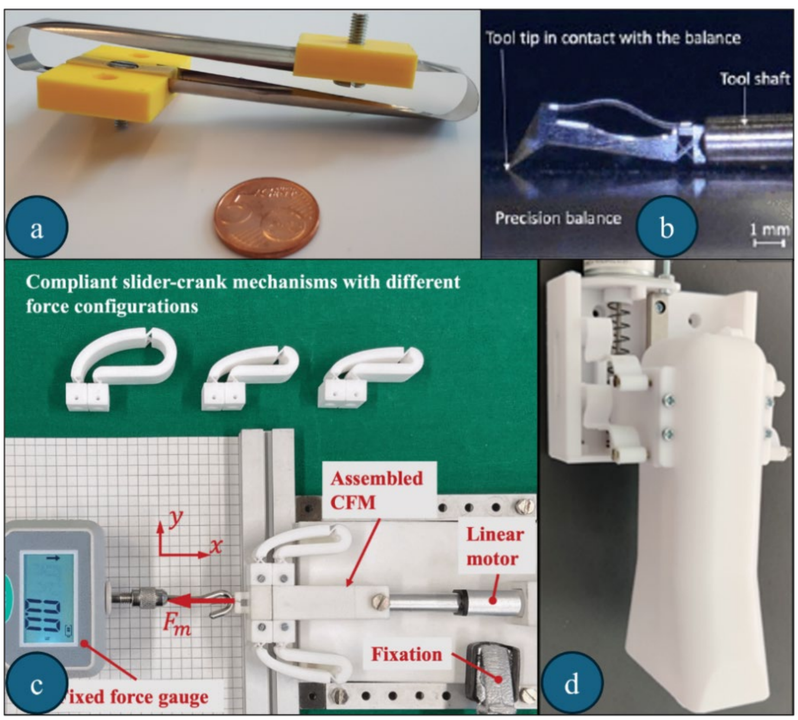

Figure 2. *Medical Applications of CCFMs (a.) Cardiac Ablation Catheter [55] (b.)Inner Ear Ossicle Tool [12] (c.) Overload protection for minimally invasive surgery [56] (d.) Constant force ultrasound probe manipulator [57]*

At this point, mechanisms from various applications (medical and non-medical) have been explored along with information regarding the mechanism's force, deflection, synthesis method, manufacturing method, and material. Common themes like the lack of geometric complexity, material complexity, and the small subset of mechanisms that exist in Table 2 reveal the lack of DfAM considerations in the manufacturing of CCFMs.

4. Discussion of Identified Themes Resulting from the Survey of CCFMs

This section discusses the commonalities and differences in the design and manufacturing methods based on AM considerations. By exploring these themes in detail, it has the potential to reveal both current limitations in the design and manufacturing of CCFMs as well as future potential when looking to make the shift to an AM-centric design and manufacturing approach.

4.1. Force and Deflection Values of Current Mechanisms are Low

Current CCFMs (seen in Table 1 and Table 2) have force values that are significantly low (less than 10 N) with a displacement that is larger than 10 mm or, in certain cases, switched to have a high force with a low displacement. There is a need for better control, higher force, and/or deflection values in CCFMs, including within the medical field. Large devices with constant force applications, such as exoskeletal devices or wearable devices, would require significantly higher force and deflection values given the larger size as compared to the devices seen in Table 1 and Table 2. At present, the only option for such large-scale devices is constant force devices using mechanical components like constant force springs, cables, and pulleys [59] due to their larger size, and higher force/deflection requirements. However, a reduction in mechanical assemblies, along with larger forces and deflections, is better due to fewer parts, negligible assembly time, low weight, reduced wear, reduced need for lubrication, and low maintenance [33].

CCFMs are generally designed and manufactured for a specific application. However, there are generalizations in the synthesis of CCFMs that allow for using pre-existing baseline designs for new mechanisms. For example, the constant force pseudo rigid body model of the slider crank mechanism developed by Howell et al. [60] has been used in the Y-Flex by Howell and Magleby [61] and by Bilancia and Birselli [62]. By pairing the existing library of CCFMs with AM for ease of adaptability, some of the CCFM designs seen in Tables 1 and 2 could be adapted to newer devices. Similarly, if existing mechanisms are to be adapted for use in different applications, they might need to be scaled up or down depending on the application. Changing the geometry of a CCFM can change the force and deflection. As an example, increasing the width of a flexure will increase the amount of force required to actuate without changing the deflection, while changing the thickness will affect both the force and deflection. While scaling is one possible solution to adapting current mechanisms for different applications, it is important that DfAM considerations be accounted for. Notably, all AM systems have a minimum feature threshold, which represents the smallest feature they can reliably produce. If a design is scaled down to affect its force and deflection characteristics, its smallest features may no longer be manufacturable. Conversely, if a design must be scaled up to achieve a certain force or displacement, then it may no longer fit within the allotted build volume.

4.2. Geometric Complexity is Not Leveraged to its Fullest

Geometric complexity refers to the idea of having complex design features and manufacturing them with ease using AM. Most CCFMs, as shown in Tables 1 and 2, have a planar design with one or two degrees of freedom. Alongside this, these designs also typically have large flat regions that encompass the mechanism. Given the advantages of AM, these flat regions can often be eliminated or adjusted to reduce material consumption with minimal impact on performance. For instance, in the mechanism designed by Wang and Lan [45], the area surrounding the mechanism can be latticed to reduce the number of flat surfaces without affecting the functioning of the mechanism. Similar modifications can be made for Liu and Xu [40], Liu and Xu [41], Pham and Wang [28], Che and Lan [30], and Xu et al. [49]. These changes will make these designs lighter while reducing material use and the time required to build them, which in turn makes them better for manufacturing using additive methods.

Topology optimization is one method by which the weight in the produced CCFMs could be further reduced. Topology optimization creates organic geometries that are often difficult to manufacture using traditional manufacturing. As seen from Table 1, Weight et al. [46], Liu et al. [48], Tong et al. [50], and Liu et al. [54] have used topology optimization to design their CCFMs. Liu et al. [48], Tong et al. [50], and Liu et al. [54] use MEX processes to manufacture the designs with TPE/ABS as materials. As manufactured, the three-finger gripper by Liu et al. [54] has a force value of 41.9 N over a 15 mm displacement range which is significantly higher than most mechanisms in Table 1. Several different topology optimization algorithms have been used to manufacture CCFMs [63–65]. The integration of topology optimization with AM from a DfAM standpoint has also materialized in the form of functionally graded lattices, support structures, and orientation optimization, along with weight reduction and material removal applications [66,67]. The optimization methods used for CCFMs are based on force/displacement optimization. Sigmund [68] proposed optimization using truss elements, while Frecker et al. [69] performed optimization using a multi-criteria approach. Meisel et al. [70] used a multi-material topology optimization approach for compliant mechanisms. CCFMs are planar mechanisms, meaning the optimization done is usually in-plane, with the out-of-plane thickness being constant throughout. However, the integration of AM combined with topology optimization could lead to parts with varying thicknesses and multi-materials for better performance.

Print-in-place assemblies can also be used to increase the use of AM's functional complexity in CCFM designs that have multiple moving parts and require assembling. This is especially true when considering the further advantages offered by in-situ embedding in AM. As an example, for the design of a cross-axis flexural pivot by Morsch and Herder [31], a print-in-place assembly could be beneficial. For Wang et al. [51], a similar approach would help reduce the number of components. Mechanisms shown in Liu et al. [48] and Xu et al. [49] are instances where AM has been used for manufacturing but not to its full potential. In the case of Liu et al. [48], use of embedding could have made the design efficient and functional in a single-piece print. Similarly, in the case of Xu et al. [49], the SMA wire can be incorporated into the design to make it a single-piece functional part. Using these principles will help with the smooth transition between the different materials leading to less points of failure.

4.3. Metals are Typically Used for Functional Devices, Polymers for Prototype Devices

As mentioned in Section 3.2, the majority of the mechanisms shown in Table 1 use metals as a material for manufacturing. Tolman et al. [47] recommends using a metal for the manufactured mechanism even though PLA was used as a prototyping material. This was also the case with Xu et al. [43]. Even though a PLA prototype is made to visualize the two stable states of the bistable mechanism, the end product was still made out of an aluminum alloy. Although AM started historically as a method for manufacturing prototypes, the use of AM for end-use products has increased multifold. Newer technologies can manufacture these mechanisms with polymers that have increased strength or use reinforcement material like continuous fiber filament deposition to improve the strength of AM parts. These new AM technologies and materials have the potential to expand the potential use of polymer CCFMs, as opposed to requiring the shift to metals.

Despite the potential future use of advanced polymer and composite materials, most CCFMs shown in Table 1 are made from metals. The reason for using metals is that metals have higher strength than most polymers. However, as long the maximum stress in a part remains within the endurance/fatigue limit of the material, the choice between metal or polymer will not impact the part. This is case-specific, and designers will have to consider the endurance limit of the material chosen. Methods to calculate this endurance limit can be found in literature [33]. As seen from examples in Table 1, metal-based CCFMs are frequently manufactured using Wire EDM. If these designs are to be adapted for AM without changing the bulk material properties, the Powder Bed Fusion (PBF) process would be ideal; PBF typically has a better resolution as compared to Directed Energy Deposition (DED) for metal AM [71]. Wire EDM has a varied range of parameters that affect the minimum feature size that can be manufactured [72]. PBF also has a minimum feature size limitation along with other AM-specific limitations like the use of supports in overhanging regions, heavy post-processing, and orientation considerations to avoid warping [73]. To successfully translate existing designs from Wire EDM to PBF, the DfAM restrictions of the AM system must be considered for the design to be realized. In case geometric alterations need to be made these will lead to a change in the behavior of the final CCFM (see Section 4.1).

Using multi-material AM might be advantageous in the case of mechanisms where different material properties are required within the same structure. For example, using a combination of rigid and flexible material in a mechanism that has a large flat region could be advantageous (Pham and Wang [28], Che and Lan [30], Liu and Xu [40], Liu and Xu [41], Wang and Lan [45], and Xu et al. [49]). Using rigid materials for the large flat regions and flexible materials for the flexures will help reduce the needed area of the large flat surfaces. However, multi-material capabilities like this are currently limited to polymer parts predominantly manufactured via MJT. One of the challenges associated with MJT materials is that the properties of proprietary polymers, such as polymers manufactured by Stratasys, are unknown and require intensive testing to determine their properties. MJT has applications in specialized areas such as dentistry [74] however, not all materials are approved for long-term implants or contact with the human body (more than 30 days) according to Stratasys' website [75]. This could impose restrictions on the use of multi-material, MJT-based CCFMs in biomedical contexts.

Another advantage of using AM over Wire EDM is that Wire EDM requires conductive metal materials. The added weight of such metals could make polymers a better choice, depending on the medical application. Polyamides (PA 2200) have been used in several compliant biomedical devices manufactured via PBF [76–78]. PEEK, a biocompatible polymer [79], has also been used for CCFMs (Wang and Lan [45]) and compliant mechanisms in space applications [80]. CCFMs manufactured using PEEK for biomedical applications warrant more research. A comparative study between MEX and polymer PBF for manufacturing PEEK cranial implants found that MEX implants were better in performance [81]. Liu et al. manufactured the model of their robotic gripper finger using MEX and TPU as material [54] and managed to get a considerably higher value for force and deflection as compared to the mechanisms in Table 1 and Table 2.

4.4. Current Medical Application CCFMs are Limited, but with Potential for Expansion

As seen from the manufacturing processes in Table 1 and Table 2, most medical CCFM's shown in Table 2 have used additive as a technique for manufacturing as compared to five out of nineteen in Table 1. This is likely due to AM's ability to cost-effectively produce customized structures, which can prove especially beneficial in a medical context. For most medical applications, the material is required to be biocompatible. Biocompatibility of fused silica, PA 2200, PLA, and stainless steel has been proven in literature [82–84]. AM has a wide variety of biocompatible materials available in MJT and PBF processes. As previously mentioned, Stratasys, a manufacturer of MJT equipment, has a range of biocompatible materials available with their machines [75]. Materials such as Titanium, Stainless Steel, and several other alloys are biocompatible and can be manufactured using PBF [85]. These materials make it possible to manufacture parts that are meant to remain in extended contact with or implanted in the human body, while also being able to leverage the geometric complexity and customization enabled by AM, as already discussed.

Medical devices require a high amount of precision in manufacturing, calling for the processes in AM with the finest feature sizes. The processes with the finest resolution in polymers are Material Jetting (MJT) and Vat Photopolymerization (VPP), whereas for metals is Powder Bed Fusion (PBF) [71,86,87]. However, VPP parts are known to undergo degradation over time [86]. MJT parts that are manufactured using biocompatible materials like MED610, MED 620, and MED625FLX are currently approved for limited-time contact with the human body [75].

Unfortunately, as the small number of example mechanisms in Table 2 suggests, current applications of CCFMs in medical devices are limited. This could be because of the reasons mentioned previously in Section 3.2. The integration of the manufacturing process in the decision-making process for CCFMs will help alleviate the concerns regarding difficulty in manufacturing and stringent material requirements. With the help of the optimization principles discussed above and rigorous testing, it will be possible to use AM to make better and more compact CCFMs that can be used for large-scale applications with requirements for higher force and deflection.

5. Conclusion

This paper identifies four overarching themes to consider while adapting existing CCFMs for manufacturing with additive techniques. These considerations are specifically linked to the themes of (1) geometric complexity, (2) material consideration, and (3) applications of current CCFMs. This paper shows that the current state of the art only allows for a specific amount of constant force within a few millimeters of displacement. The method of manufacturing has less bearing on the design choices made unless micro-scale mechanisms are involved, in which case, the precision of the manufacturing process may impact the performance of the CCFM. However, the manufacturing method can help improve the performance of the part. Current CCFMs also move in one or two dimensions. However, AM has shown that printing compliant mechanisms with multiple degrees of freedom is possible.

Future work centers on the expansion and refinement of efforts begun in this paper. As an example of this, the list of the mechanisms in this paper is not exhaustive. An exhaustive literature review of CCFMs and their manufacturing methods will help gather more data in the future. Additionally, as with any technology, AM has certain constraints. As such, it becomes crucial to develop a formal pathway for not only designing CCFMs that account for the unique opportunities inherent to DfAM, but also for incorporating AM's unique design restrictions. This pathway, which will be detailed as the scope of this study expands, will take the form of a formal framework for designing CCFMs targeted at the capabilities of AM. Finally, with such a framework established, physical printing of structures can be coupled with experimentation to further validate the benefits of combining CCFMs with AM, especially as applied to a medical context.

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7. References

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