# Tables Got Moves: A Review on Actuated Table Designs



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# Tables Got Moves: A Review on Actuated Table Designs

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## ABSTRACT

Most research on interactive table designs focuses on interactions with static digital tabletops. Relatively little research investigates the niche interactive tables with actuating capabilities. Such 'actuated tables' are tables that can physically move by changing their shape, orientation, or position. This paper aims to provide the HCI community with an overview on interactive actuated table research by reviewing literature that has appeared over the past decade. Our search resulted in a set of fifteen actuated table designs, which we reviewed with an emphasis on attributes related to the concept behind the table, the interactivity and form of the table, and the research approach used to study the table. Our analysis and results show that most tables offer adaptability, flexibility, and social mediation through their ability to actuate. We report on the four identified 'actuation forms' based on the various actuation styles found in current designs. We conclude by outlining gaps for future research, such as utilizing the expressivity that can be conveyed through the table's actuation as a design resource, and exploring more application areas that can benefit from the qualities of actuated tables.

## CCS CONCEPTS

• **Human-centered computing → Interaction design**.

## KEYWORDS

actuated tables, interactive tables, shape-changing interfaces, actuated interfaces, literature review

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## 1 OVERVIEW AND RELATED WORK

Interactive surfaces are becoming increasingly more embedded in our everyday lives. One emerging field of interactive surfaces that has seen new developments over the last decade is interactive tables. Generally speaking, these are physical table-like artifacts with computational abilities, made interactive through digital enhancements. This field has a long-standing history in both academia and industry, dating back to the early 1990s [27].

So far, most academic work on interactive tables has focused on interactive *tabletops* – interaction with the large horizontal surface segment of the table. Prior review papers on interactive tabletops show three recurring types of tabletop interfaces [3, 26]: Digital-, Tangible-, and Actuated Tabletops (Figure 1). Digital tabletops are tables with a large graphical user interface embedded into the tabletop. These graphical interfaces enable interaction through multi-touch displays [12, 45] or the combination of a tracking depth-camera and a projector [5, 36]. These systems are united through the finger-touch and gesture interaction style they offer their users, similar to a present day tablet. The second type of tabletop research is characterised by a more tangible interaction style, largely influenced by the increased popularity of tangible user interfaces (TUIs) around the 2000s. These tables allow for a more tangible interaction style mediated through so called tangibles or "phicons" [44], which are physical objects or pucks used as input for interaction using camera-tracking. The reacTable [15] is an example that popularised this tangible interaction style. The third type of tabletop is what we refer to as an actuated tabletop, and can be seen as the precursor to the interface type we examine in this article. Inspired by the vision of "Radical Atoms" [13] and the developments in Actuated Tangible Interfaces [34], there has been a line of research where the interactive system can physically actuate shapes on its tabletop. Examples include the Actuated Workbench [31], Relief [21], inFORM [6], and TRANSFORM [14]. These devices are composed of an array of physical motorised "pixels", together forming a dynamic platform that sets the physical pixels (atoms) in motion through actuation.

While prior reviews on interactive tables have focused on the tabletop [3, 18], little research focuses on interaction with tables in their entirety – beyond the tabletop surface (with [50] as a notable exception). Driven by developments in shape-changing interfaces [1, 4, 35] and robotic furniture [39] over the last decade, we have observed a growing body of work towards the research and development of a more holistic shape-changing type of interactive table, which we refer to as "actuated tables". Actuated tables are table-like interfaces with capabilities to kinetically change their physical shape, position, composition, orientation, and location. In contrast with static tabletops, actuated tables offer unique opportunities by physically adjusting itself and adapting to specific and dynamically changing situations, environments, and users. Thus, we anticipate future research to incorporate more and more actuated mechanisms within interactive tables that can support their users.



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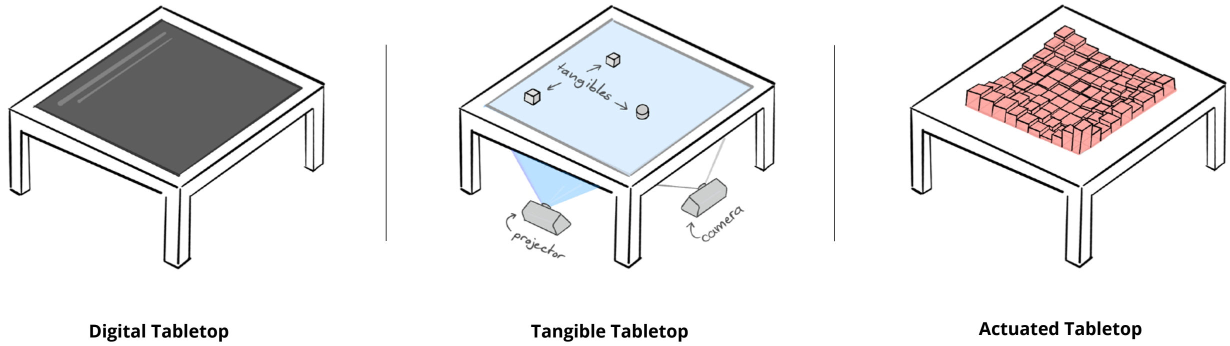


**Figure 1: Three recurring styles of interactive tabletops: digital, tangible, and actuated tabletops.**

This has motivated us to create an overview of the current state of the art on “actuated tables”. To the best of our knowledge, this is the first work that addresses a review of literature on actuated interactive tables. Hence, the main purpose of this work is to provide the community with a broad baseline of the current state in actuated table research that can act a starting point for future research. In summary, our contributions to the research community are: a review of literature on interactive tables with a focus on tables with kinetic actuation abilities; an overview of aspects related to the actuated table’s design concept and application, the build and design of the table, and the research approach to study the table; and a set of future directions that one can consider in researching actuated tables.

## 2 METHOD

The aim of our literature review is to build an understanding of research conducted in the area of actuated interactive tables, focusing on aspects that relate to the context of use, the table design and form, and research approaches. To achieve this, two of the authors searched for, collated, and analyzed a set of literature within the umbrella domain of Human-Computer Interaction (HCI). The following outlines the details of our approach.

**Literature source:** We utilized the ACM Digital Library (DL) to collate a representative set of relevant papers for our review. The ACM DL captures main research articles that represent a variety of disciplines within HCI research, and have been previously utilized for other HCI literature reviews as their main search source [32, 38, 47]. Here we note that we did not gravitate towards the IEEE repository as we are not interested in the technical aspects of actuated tables and purely focused on the HCI and design-related aspects of actuated tables, which are more common in the ACM DL.

**Term search:** Since the term “actuated table” has not been clearly established and articles might have used broader terms to describe the type of interactive tables we aimed to include in this review (such as kinetic table, robotic table, and shape-changing table), we first ran a broader search in the ACM DL on the keywords “table”, “tabletop”, “design*”, and “interact*”. This allowed us to capture an initial set of 198 research papers (from January 2012 to December 2022).

**Collated Set:** To collate a set of representative papers that address the main aim of this literature review, we established the following exclusion criteria:

- A research publication must be either a research-article, demo report, or extended abstract (this includes late breaking reports, work-in-progress, or poster papers). Review or survey papers were excluded but crawled to search for missed table designs.
- In case of overlapping work similar to another publication, such as publications from the same research group describing the same design, the most substantial publication was included in the review. For example, a full paper including a study of the work was selected over a preliminary demo publication.
- The publication must include a design concept and a prototype of an interactive actuated table.
- Publications reporting on actuated interfaces that are physically separated from the table were excluded.
- Publications focusing merely on the technological implementation (such as the technical development of models, frameworks, algorithms, etc.) rather than the general interactivity were excluded.

We screened through the collated set of the 198 papers against the agreed exclusion criteria by reading the titles and abstracts. When unclear, we studied the content of the article in more detail. We worked closely throughout the initial scan on the 198 papers and discussed any uncertainties. These discussions helped to shape a clearer understanding of what sort of actuated table we were looking for in this review and were instrumental in shaping the exclusion criteria. For example, when discussing interfaces such as (Dis)Appearables [29] and Zooids [19] we excluded all papers where the focus of interaction was on actuated interfaces that operate physically separated from the table.

We initially started off by looking into full research articles as they tend to include an empirical evaluation of the design, which is one of the research directions we wanted to review. However, since our search led to only 11 full-articles, we decided to perform

**Table 1: A summary of the review categories, the coding attributes, and their descriptions.**

| Category | Description |
|---|---|
| **Concept-centered** | |
| Application | What is the intended purpose behind the table design? |
| Context | Who is the table designed for and in what environment is the table situated? |
| Single or Multiple User(s) | Is the table designed with a single or multiple users in mind? |
| **Table-centered** | |
| Actuation Form | What actuation capabilities does the table posses - how can it change its form? |
| Interaction Modalities | How does the table sense its environment (input) and what does it actuate (output)? |
| Aesthetic Motivations | Are the aesthetics of the table design explicitly mentioned and motivated? |
| **Research-centered** | |
| Research Approach | How does the table design generate new knowledge (Lab, Field)? |
| Degree of Independence | To what extent is the table developed to operate independently? (Autonomous, Wizard of Oz) |

reference crawling and broaden our search criteria to include demo reports and extended abstracts. This expansion led to four additional articles. One article originated from a publisher outside of the ACM Digital Library (Springer, [41]) and the other three publications were extended abstracts [7, 23, 24]. Even though the extended abstracts and demo reports did not include an evaluation of the design, they did bring forward a clear design concept and description of the build of the table. After these two expansions to the selection, we arrived at 15 articles on actuated table designs to review. The final set of papers were published between 2013 and 2021 in seven different academic venues (AH, CHI, DIS, INTERACT, ISS, ITS, TEI).

**Categories and Coding:** Assuming this is the first review on actuated table designs, we decided to keep our scope of review categories broad and high-level to help situate this specific type of interactive table in the context of HCI research. Our review orients around three main review categories with corresponding coding attributes that relate to actuated tables. These are: concept-centered, table-centered, and research-centered.

By concept we refer to the researchers' intended or envisioned purpose and application of the design, the environment the table is situated in, who the intended user group is (if any), and if so, whether the table serves a single or multiple users. This was motivated from previous work, where Zum Hoff et al. [50] point out the lack in prior research in the classification of interactive tables based on their application.

The second category, table-centered, examines the attributes related to the design and build of the table itself. Since all tables possess some kinetic form of actuation, we wanted to examine if there were any similarities or techniques in how the table actuates and what the form of actuation affords to the user, context, or research purpose. Second, we wanted to gain insight into what interaction modalities were used to sense input from the user or environment, and what technologies were used to generate the output (or actuation form). The final attribute related to the design of the table is the aesthetics. Similar to Zum Hoff et al. [50], we were mainly interested in the rationale and discussions behind the design choices of the aesthetics, such as motivations related to the static appearance through form, material, finish, but also motivations regarding the aesthetics of interactivity, such as dynamic form changes.

The third category considers the research-centered attributes, where we investigate how the actuated tables are used in HCI research. To arrive at a compact and comparable overview, we summarized the research methods based on two general research approaches – lab and field studies – and elaborate on how the table was used to generate new knowledge. If the research approach contained an empirical study using the table artifact, we were interested in the degree of independence each artifact had in the study. We were interested to find out whether the artifact can function autonomously or requires manual assistance of the research team (Wizard of Oz (WoZ)). The guiding review categories, coding attributes, and their descriptions are summarized in Table 1 and further unpacked in Section 3.

**Analysis:** To analyze the collated set of 15 publications, we created a coding scheme containing the categories listed above. Two researchers read each article individually, coded them and thereafter discussed their analysis to verify the final coding and come to a common understanding. The result of this process and a final overview of the coded data are represented in Table 2, which lists the 15 publications. For the sake of clarity, we will use the named table design to refer to specific papers throughout the remainder of this article. In the cases of [8, 20, 24, 42], the table artifact was not given a name. For these articles, we chose a name derived from the title of the article. The list is formatted based on publication date, from most recent to oldest.

## 3 RESULTS

In this section, we present the main findings based on the coded data in Table 2: concept-centered, table-centered, and research-centered.

**Table 2: An overview of the gathered data set on actuated tables, covering concept-centered, table-centered, and research-centered attributes.**

| | Concept-centered | | | | | | | | | | | | | | Table-centered | | | | | Research-centered | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Application | | | | | Setting | | | | | | | User(s) | | Actuation Form | | | | | Approach | | | Independence | |
| | Collaboration | Ergonomics | Healthcare | Inquiry-driven | Social | Dining | Healthcare | Home | Work | Generic | Indoor | Outdoor | Single | Multiple | Actu. Tabletop | Mobile | Height-change | Shape-change | Aesthetics | RtD | Lab | Field | Autonomous | Wizard of Oz |
| [49] **DeformTable** | ○ | ○ | ○ | ● | ○ | ○ | ○ | ● | ○ | ○ | ● | ○ | - | - | ○ | ○ | ● | ○ | ● | ● | ○ | ● | ● | ○ |
| [9] **KirigamiTable** | ● | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ● | ○ | ● | ○ | ○ | ● | ○ | ○ | ○ | ● | ● | ● | - | - | - | - |
| [7] **TurnTable** | ● | ○ | ○ | ○ | ● | / | | | | | ● | ○ | ○ | ● | ● | ○ | ○ | ○ | ○ | ○ | - | - | - | - |
| [23] **SociaBowl** | ● | ○ | ○ | ○ | ● | / | | | | | ● | ○ | ○ | ● | ● | ○ | ○ | ○ | ○ | ○ | - | - | - | - |
| [20] **Auto-Desk** | ○ | ● | ○ | ○ | ○ | ○ | ○ | ○ | ● | ○ | ● | ○ | ● | ○ | ○ | ○ | ● | ○ | ○ | ○ | ● | ○ | ○ | ● |
| [17] **AdapTable** | ○ | ● | ○ | ○ | ○ | ○ | ○ | ○ | ● | ○ | ● | ○ | ● | ○ | ○ | ● | ○ | ○ | ○ | ○ | ● | ○ | ● | ○ |
| [28] **ActuEating** | ○ | ○ | ○ | ○ | ● | ● | ○ | ○ | ○ | ○ | ● | ○ | ○ | ● | ● | ○ | ○ | ○ | ● | ● | ○ | ● | ● | ○ |
| [46] **ActiveErgo** | ○ | ● | ○ | ○ | ○ | ○ | ○ | ○ | ● | ○ | ● | ○ | ● | ○ | ○ | ○ | ● | ○ | ○ | ○ | ● | ○ | ● | ○ |
| [42] **Interactive Interior** | ○ | ○ | ● | ○ | ○ | ○ | ● | ○ | ○ | ○ | ● | ○ | ○ | ● | ● | ○ | ○ | ○ | ○ | ● | ○ | ● | ● | ○ |
| [11] **Table-non-table** | ○ | ○ | ○ | ● | ○ | ○ | ○ | ● | ○ | ○ | ● | ○ | - | - | ○ | ● | ○ | ○ | ● | ● | ○ | ● | ● | ○ |
| [8] **Proxemic-Trans** | ● | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ● | ○ | ● | ○ | ○ | ● | ○ | ○ | ○ | ● | ○ | ● | - | - | - | - |
| [24] **Eating Together** | ○ | ○ | ○ | ○ | ● | ● | ○ | ○ | ○ | ○ | / | | ○ | ● | ● | ○ | ○ | ○ | ○ | ○ | - | - | - | - |
| [41] **MovemenTable** | ● | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ● | ○ | ● | ○ | ○ | ● | ○ | ● | ○ | ○ | ○ | ○ | ● | ○ | ○ | ● |
| [43] **ART** | ○ | ○ | ● | ○ | ○ | ○ | ● | ○ | ○ | ○ | ● | ○ | ○ | ● | ● | ○ | ● | ○ | ○ | ● | ○ | ● | / | |
| [40] **TransformTable** | ● | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ● | ● | ○ | ○ | ● | ○ | ○ | ○ | ● | ○ | ○ | ● | ○ | / | |

**Legend: ● = yes, ○ = no, - = not applicable, / = not specified.**
**Please refer to Section 3.2 for a summary of the Interaction Modalities**

## 3.1 Concept-centered

**Application Areas -** Our results show five different application areas addressed in the literature of actuated tables. *(1) Collaboration:* Collaborative applications represented the largest portion with six out of fifteen papers. A common thread between four of the six papers [8, 9, 40, 41] is that they share the same purpose of adapting to the users' task at hand by dynamically changing the physical form of the table to promote a flexible workspace by transitioning between a group and individual workspace. On the other hand, SociaBowl [23] and TurnTable [7] aim to improve collaboration by strengthening the social dynamics in group settings by having a physical artifact mediate turn-taking, equalizing the verbal communication. *(2) Social Dining:* Eating Together and ActuEating [24, 28] situate themselves in a social dining setting. Eating Together [24] augments a dining experience between two individuals to nudge the users to complete their meals at a similar pace. ActuEating [28], on the other hand, sets out to explore the aesthetic opportunities of shape-change in decorative artifacts embedded within complex social settings such as social dining. *(3) Healthcare:* Two papers report on designs deployed in a healthcare settings. They also can be considered to take an accessibility standpoint, explicitly showing awareness and consideration to user needs related to accessibility. The Assistive Robotic Table (ART) [43] is specifically designed for older and post-stroke adults to augment their rehabilitation and improve the caregiver's productivity. This design uses its actuating capabilities for the sake of adaptability and manoeuvrability so that it is able to accommodate drastic changes in the users' capacities over time. The Interactive Interior [42] is designed to support sensitive consultations between healthcare personnel and patients in a hospital oncology department. In their work it also mentions accessibility as an important design consideration, on the grounds that equal accessibility of the digital resources on the table invites better doctor-patient collaboration and discussion [42]. *(4) Inquiry-driven:* Table-non-table [11] and DeformTable [49] are two table-like artifacts designed to challenge the purpose of usefulness by design, actively avoiding specific use goals and user groups. Deployed to coexist in domestic households, these artifacts are designed to incite curiosity, exploring new interactions and appropriations between humans or non-humans and the artifact [49], or to advance design theory and methodology [11]. Finally, *(5) Ergonomics:* AdapTable [17], Auto-Desk [20], and ActiveErgo [46] had a more generic representation of the application areas. These works are all designed for single users, aiming to improve an individual's health by providing a more ergonomic work station setup. ActiveErgo senses an individual's body-metrics and automatically adjusts the computer-monitor, desk, and chair's positions based on posture ergonomics standards. Auto-Desk encourages its users to vary their posture by automatically changing the desk's height on a computer. AdapTable is designed to address the physical discomfort of reaching content on large interactive tabletop displays.

**Single or Multi User Setup -** Ten out of fifteen tables are designed for scenarios of use that involve more than one user. For example, Eating Together [24] is conceived for two users sitting on opposite ends of a dining table. ActuEating [28], which is also set in dining context, is designed for group settings and affords a formation that gathers around the table with the artifact as the centrepiece. Tables such as Proxemic-Trans, KirigamiTable, Interactive Interior, and TransformTable [8, 9, 40, 42] are influenced by social psychology theories of proxemics; the study of human use of space and its effects on communication and social behavior [10], and F-formations, which is about the layout of formations and orientation between people to encourage different forms of social dynamics [16]. These table designs use their actuating capabilities to afford fluidity in formations around the table, as opposed to fixed formations in static non-actuated tables. Three out of fifteen papers (AdapTable [17], Auto-Desk [20], and ActiveErgo [46]) are designed with a single user in mind. ActiveErgo and the Auto-Desk are both adaptations of an ordinary office desk setup where the user stands or sits on a height-changing desk with a monitor. The two inquiry-driven designs [11, 49] have no specific target user and can be any human or non-human within the household environment.

## 3.2 Table-centered

**Actuation Forms -** The common denominator between all tables in this review is the ability to set the physical in motion through actuation. However, the way in which the tables move and what parts of the table can move varies. We identify four generalizable kinetic formation changes in the 15 table designs described in the collated literature, categorized based on the manner in which the table kinetically changes its physical shape, position, or layout (see Figure 2). We refer to these four formation changes as 'actuation forms'.

*(1) Actuated Tabletop:* In this form, the actuation of the table happens in or on the tabletop, while the body of the table remains static. The table as an entity does not move, but the content on the tabletop does and thereby draws the attention of the user(s) towards the center of the tabletop. We found five examples of this form of actuation (ActuEating [28], Eating Together [24], Interactive Interior [42], SociaBowl [23], and TurnTable [7]). Four of them (Eating Together, Interactive Interior, SociaBowl, and TurnTable) have mechanically interactive elements built into the tabletop, whereas ActuEating [28] is an external design that is positioned on top of a non-interactive table.

*(2) Mobile:* Here, the entire table can relocate itself in the physical space by moving in a horizontal x-and-y orientation, whilst retaining its original shape and composition. Both Adaptable [17] and MovemenTable [41] are examples of multiple individual units of multi-touch displays on wheels that can move away from another and towards each other to provide flexibility in spatial arrangements of large tabletop touchscreen layouts. Table-non-table [11] is similar in its actuation as it moves its entire body once or twice a day for less than ten seconds, using this unexpected actuation to divert assumptions about interactions with everyday objects such as a static table.

*(3) Height-change:* This actuation form consists of tables capable of moving their tabletops vertically along the z-axis, changing the height of the tabletop whilst remaining the original shape and orientation. Examples of this form of actuation are ActiveErgo [46] and Auto-Desk [20], which both use height-changing actuation to adapt the tabletop height to individual office workers with the goal of providing a more ergonomic desk setup.

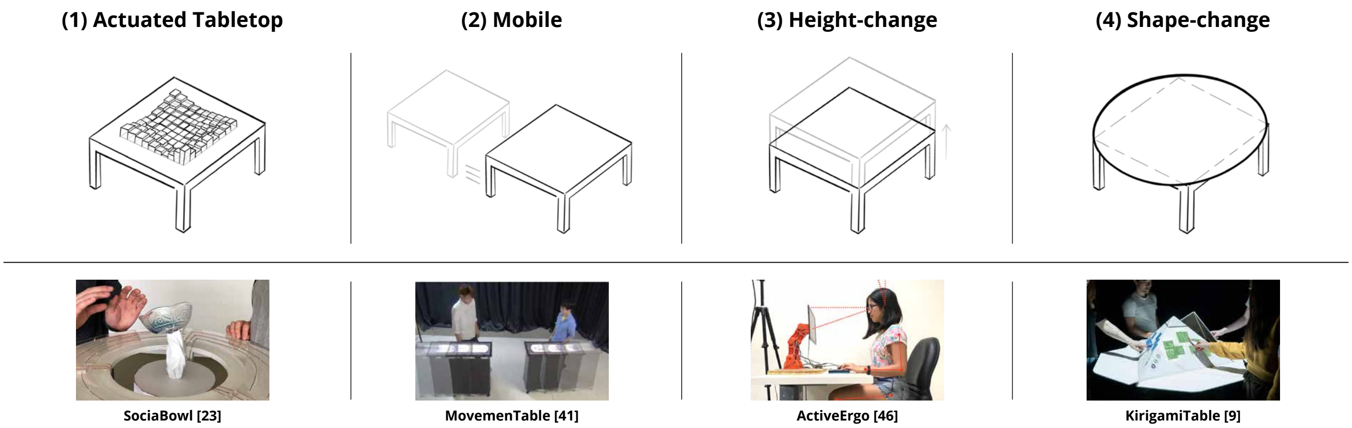


**Figure 2: Illustrations of four actuation forms: Actuated Tabletop, Mobile, Height-change, and Shape-change. (Images are reproduced with permission from the corresponding authors)**

*(4) Shape-change:* The last actuation form uses shape-change to transform the table structure or tabletop surface into a different shape, layout or orientation. In TransformTable [40], the flat tabletop surface can mechanically change shape between a square, circular, and rectangular layout without changing its height or position in the physical space. Similarly, KirigamiTable [9] changes its horizontal shape between circular and semi-circular, with the addition of 3D deformations through folding its tabletop structure into three different configurations. Proxemic-Trans [8] uses actuation to transition between a flat surface between a horizontal (tabletop-like) and vertical (wall display) position. What these interfaces have in common is that their tabletop is not one solid flat surface but is broken down into multiple surfaces that can together be deformed into multiple configurations in different shapes and inclinations.

**Interaction Modalities -** Regarding input interactions used, we found two tables that rely on the weight of external objects as input (Eating Together [24] and DeformTable [49]). We found several table designs that use graphical touch-based interfaces to instantiate the actuation form [9, 17, 41]. What these examples have in common is that the primary work of the user is centered around a graphical user interface; either a multi-touch display or a projector-camera based setup. Here, a graphical touch menu shows options to change to a different physical formation. Next, we found the use of capacitive touch sensors embedded in ActuEating [28] to detect close-ranged proximity between people or objects and the table artifact. SociaBowl [23] also uses multiple capacitive touch sensors laid out in an array to detect touch based hand gestures on the table. ActiveErgo [46] uses skeletal motion tracking to detect an individual's posture, while TurnTable [7] uses microphones to respond to the volume of people's voices. Finally, we see two examples of tables adapting to the user(s), triggered by a change of event from the user or the proxemic formation of people gathering around the table. In Auto-height Change [20], the tabletop's height changes when a user shifts to a new task on a desktop computer. TransformTable [40] changes the shape of the table when it detects a change in the number of people present around the table. Regarding the output, each table design possesses at least one of the four actuation forms (Section 3.2). Multiple height and shape-changing table designs use linear actuators that can extend and retract a shaft in a linear direction. Such motors are used to control the height and position of the tabletop in [8, 9, 20, 43, 46, 49]. TurnTable [7] and ART [43] use pneumatics as a driver for actuation. For instance, TurnTable [7] contains five distributed inflatable airbags embedded in the tabletop and hidden from the user behind a stretchy fabric, to dynamically set an inanimate ball in motion by inflating and deflating individual airbags.

**Aesthetic Motivations -** ActuEating [28], table-non-table [11], deformTable [48, 49], and KirigamiTable [9], demonstrate proactive consideration of the aesthetics of the table artifacts and provide a substantial description of the design choices that informed the aesthetics. In ActuEating, the key focus of the research is to explore the aesthetics of shape-changing decorative artifacts in everyday life. The article provides rich descriptions on the motivations behind the aesthetics, such as designing the movements of the actuation to be slow, silent, and subtle to create an organic appearance, as opposed to a previous prototype that was more mechanical. On the other hand, the Table-non-table and DeformTable are both designed to be research products rather than prototypes [30], which implies that they are crafted to a finished quality. This is to ensure that the actuated tables are treated as 'what is' and not as 'what could be', which is symbolised through the unfinished look of a prototype. Moreover, in the case of Table-non-table, their design draws on the familiarity of paper sheets and the uses we associate with these such as drawing, but then distorts it with an uncommon square format and a cutout in the middle. Following the same ethos of balancing familiarity and unfamiliarity, DeformTable [48] is designed to have an inconvenient table height to spark curiosity and afford appropriation. Their article facilitates descriptions of aesthetic decisions such as using a white colored flexible fabric with a dotted perforated pattern to accentuate the movements when shape-changing. KirigamiTable [9] provides details on how experimenting with various Kirigami structures influenced the dynamic form changes of the table design. Furthermore, they list three strategies in how the appearance of the table can communicate an anticipated shape-change transition between individual and group work. Outside of these four papers, none of the other articles provide an elaborate account of the aesthetic motivations in their work. However, this doesn't mean that aesthetics is completely neglected. For instance, MovemenTable [41] touches upon aesthetics as it draws inspiration from cartoon-animations to design expressive animation on its display to signal motion cues, but does not provide any descriptions of the aesthetic motivations behind the physical build.

### 3.3 Research-centered

**Research Approach -** Seven articles explicitly mentioned adopting a Research-through-Design approach. KirigamiTable, Proxemic-Trans, Interactive Interior, Table-non-table, and DeformTable [8, 9, 11, 42, 43, 49] referred to this as "Research-through-Design"; Interactive Interior [42]) refers to the same research approach as "Constructive Design Research", and ActuEating [28] as "Design-led exploration". Ten out of fifteen publications used a design research approach that includes an evaluation of the actuated table. Half of these are done in a controlled lab setup (AdapTable, MovemenTable, TransformTable, ActiveErgo, Auto-Desk [17, 20, 40, 41, 46]); the other half in a field context (ActuEating, Interactive Interior, Table-non-table, DeformTable, ART [11, 28, 42, 43, 49]). The remaining five publications had no evaluation.

The lab studies typically examine matters of usability, such as task completion and performance. For example, AdapTable [17] evaluates the user's performance in terms of efficiency and workload, and MovemenTable [41] examines whether users understood the cues from their design and if the table was helpful. ActiveErgo [46] compares the ergonomics in its design against conventional desk setups in terms of speed and accuracy, and Auto-Desk [20] measures aspects such as Frustration, Engagement, and Mental effort when interacting with levels of automation in their design.

From the field studies, Table-non-table [11] and DeformTable [49] are deployed in the wild for long-term periods. Table-non-table has been deployed for a total of four and a half years through six instances of deployments in different households, and DeformTable has been deployed for long-term studies (at least five months) in five households. ActuEating [28] reports on four field deployments in various dining settings where participants could interact with the artifact in an exploratory manner. These deployments were followed up with critique sessions, where the users provided feedback and came up with improvements for further design of the artifact.

Moreover, the KirigamiTable [9] and Proxemic-Trans [8] did not use their design to evaluate with external users, but provide new knowledge by reflecting on their design process and design choices to distill a set of interaction techniques that are worthwhile considering when designing shape-changing tables with a focus on proxemics.

**Degree of Independence** From the collated set, six actuated tables were deployed completely independently (DeformTable [49], AdapTable [17], ActuEating [28], ActiveErgo [46], Interactive Interior [42], and Table-non-Table [11]). These actuated tables required no intervention from the research team to fully realize the intended design functionality. ActuEating reports on adding agency to the artifact: "Agency was also enabled in the algorithm of ActuEater2 to display autonomous actuations if ignored for sometime." Nabil et al. [28]. Both Table-non-table and DeformTable are deployed for longitudinal field studies, for which a high degree of independence is deemed a necessity. MovemenTable [41] and Auto-Desk [20] made use of the WoZ technique to manually simulate the automation of the table. Both designs chose the Wizard of Oz setup since due to the technical challenges of accurately sensing nuanced user behaviour. In Auto-Desk [20], the researchers adjust the table height manually when they observe the user changing work-related tasks on their desktop computer. MovemenTable [41] used the WoZ technique to simulate the table's situational awareness and to manually control the movement of the table, such as following a walking person or approaching a shy person.

## 4 DISCUSSION AND FUTURE WORK

In this section, we discuss the patterns and insights found in the data (Section 3), outline gaps in current research, and suggest promising avenues for further research.

**Qualities of Actuation in Interactive Tables:** We found the core qualities that drive actuated table designs and research to be *Adaptability* and *flexibility*. In this context, adaptability can be seen as examples of tables that can adapt their physical shape, position, layout, or orientation, based on the user's tasks at hand (e.g. [17, 40, 41, 43]), or bodily posture (e.g. [20, 43, 46]), whereas flexibility in actuated tables can offer modularity by shifting between different formations and shapes. The shape-changing functionality allows one actuated table to fulfil multiple purposes using one artifact, minimizing the need for multiple tables [8]). Examples of tables in this review that offer flexibility are the ones that possess the actuation forms *Mobile* and *Shape-change* [8, 9, 17, 40, 41, 43].

The core qualities found in our review can enable abilities that may not be possible in other interactive tables. For example, the ability of changing shape enabled a unique strength in an actuated table by allowing it to encourage social interaction between people around the table, thus taking a *Social mediation* role (e.g. [24] [42][23][7]). This in turn also opens up future research opportunities to investigate other abilities that the core qualities of actuated tables can be utilized in, to provide unique setups and contexts.

**Need for More Applications:** From the data we observed five applications of actuated tables (collaboration, ergonomics, healthcare, inquiry-driven, and social purposes), with a relatively narrow diversity in use scenarios. We were surprised to observe the absence of some applications, including gaming, accessibility, and education, that are adequately represented in digital and tangible tabletop research. For instance, there is a substantial amount of research conducted on tabletop games in interactive tabletops (e.g. [2, 22, 33]) and there are many situations in which gaming could benefit from actuation. Furthermore, we see more opportunity in designing actuated tables for accessibility purposes. In this review, the two tables in the healthcare domain adopted a design process with accessibility as a core concern. We can foresee that the aforementioned qualities of actuation, especially its ability to physically adapt to the user, could be used for people with various physical disabilities.

**Actuated Tables in Outdoor Settings:** Interestingly, our results show that all actuated tables in this review are designed for an indoor environment. A possible explanation for this would be to spare the research artifact from damage or wear and tear due to unpredictable factors in the outdoor environment such as weather, as well as the risk of people vandalizing the technology when deployed in an outdoor public setting. Also, in order for the actuated table to utilize its interactive properties it most likely needs to be powered electronically, which comes with its own obvious limitations for researchers. A battery powered design needs charging, and a connection to the grid could limit its flexibility in terms of placement. Nonetheless, as seen in our results, current research is missing out on interesting use cases for actuated tables outdoors. Future research directed towards fabricating a technological table that is outdoor-proof, that is robust and resilient in build, can open up for several outdoor research contexts. The agency of an actuating table could for instance be used in novel ways to bring people together in public spaces such as parks, sports fields, and playgrounds. For example, the table's agency could be used to entertain people while idling at public transportation stops.

**Actuation Forms:** One of the main contributions in this review is the proposed four actuation forms (Section 3.2). We argue that these categories can help researchers get a better understanding of how different forms of actuation can be utilized depending on the purpose and goal of the design. Furthermore, we hope that design practitioners can find inspiration for the design of future interactive tables using actuation. We do not claim this as a definitive set of categories, as there can undoubtedly be more forms of actuation possible with the technical advances in actuated interfaces. Future research in actuation forms can be utilised to seek further adaptive and flexible structures that can serve users in different contexts – opening up for more actuation categories. In addition, more empirical work on the design of actuated tables is needed to motivate the use and applications of the different actuation forms.

**Expressivity through Actuation:** In our analysis, we found two examples that used motion design as a means of expression. SociaBowl [23] uses anthropomorphic animations of movement to add personality to its design. For instance, the prototype bows to a user as a formal expression to invite them to interact with the system. The design also uses wobbly motions to portray the table in a more playful manner. MovemenTable [41] also draws inspiration from animations by adding motion cues to indicate the direction of where the table is going to move next. However, the animation design here is not implemented in the physical motion of the table, but is digitally simulated in its graphical interface by warping the content on its screen. The idea of designing behavior and expression in interactive products and robots through movement has been explored in HCI and Human-Robot Interaction (HRI). Examples include Sirkin et al. [39], who designed a piece of robotic furniture with behavioral motion to engage people; Ross and Wensveen [37], who designed behavior in a desktop lamp informed by improvisational dance, and Miyoshi [25], who explored *kinaesthetics*; the aesthetics of objects in motion. The foremost quality of actuated tables is their ability to physically move or change shape. We foresee potential in leveraging this movement to design aesthetic experiences with interactive tables by orchestrating properties related to motion, such as speed, acceleration, and direction. Such motion designs can fulfill utilitarian purposes, like adding a dimension of communication to robotics through motion (similar to body language), as well as aesthetic, playful, artistic, and poetic purposes.

**Limitations and Further Work:** While our review provides a broad yet comprehensive overview of actuated table designs, we also recognise a missed opportunity in delving deeper into the individual review categories. For instance, it would be useful to expand the analysis and discussion of research methodologies to encompass data collection methods and analysis methods. Such discussions could guide fellow researchers in choosing appropriate methodologies to further investigate this niche area of research.

We already suggested future research directions based on gaps in the literature; designing for more application domains and outdoor settings, and working with expressivity through actuation. We also found important gaps – not in the literature, but in the research – that offer promising avenues for other researchers. First, we see an opportunity in developing more open-source prototyping tools since actuation can be complex to prototype, especially when designing for expressivity. Furthermore, tables can be rather large objects to fabricate, requiring a lot of physical resources. Future research can also consider smart ways of incorporating scale-models, and virtual or mixed-reality simulations to overcome the resource problem. Finally, we see untapped potential in researching the complexity and multiple facets connected to accessibility in regard to interactive table design. We are convinced that especially the adaptive and flexibility qualities of actuated tables can be exploited more to provide a more optimal experience for people with various abilities.

## 5 CONCLUSION

The purpose of our study was to lay out the state of the art within HCI research on actuated tables over the last decade. We defined actuated tables as an interactive table with the ability to physically move itself, or a part of itself, through kinetically changing its shape, position, composition, orientation, or location. Our review consists of a corpus of fifteen research articles including an actuated table design, which were analyzed to provide a general overview encompassing concept-centered, table-centered, and research-centered attributes. Although the current study is based on a small sample of works, we found that the most common qualities of actuated tables are their adaptability, flexibility, and agency as a social mediator. Based on the variety in types of actuation, we derived four preliminary forms of actuation: *Actuated Tabletop, Mobile, Height-Change, and Shape-change*. We identified gaps in current research where the potential of actuation in tables is underexplored, including applications related to accessibility, gaming, and tables in outdoor settings. Finally, we suggest how the movement of actuation can be further explored as a design resource to add expressivity to interactive table design.

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