Proceedings of the 5th International Conference on Interdisciplinary Humanities and Communication Studies
DOI: 10.54254/2753-7064/2026.37031

Embodied Situatedness: A Dynamic Framework for Critical Reflection in Data Physicalization

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Abstract. Physicalization makes data tangible. However, understanding and engagement are not sufficient in themselves to ensure that people question the social and political contexts in which data is produced. This paper addresses the question of whether and how embodiment and situatedness can be dynamically employed to move people beyond understanding data to reflection on it. Based on an analysis of seven exemplary projects, this research explores how the dimensions of embodied interaction, material response, context, and culture affect people's understanding of data. The analysis demonstrates that embodiment allows for contestation of data by making it tactile and kinetic, while situatedness adds moral and political weight to data by grounding it in the places where the consequences of the data arise. Together, the dimensions produce a friction between sensual experience and meaning, enabling questioning of authority, accountability, and power relations rather than passive consumption of data. Based on these results, the paper develops a framework with three design guidelines for data physicalizations: juxtaposition of comfort with criticism, placement of physicalizations in contentious contexts, and use of expressive forms to make processes invisible in the data visible.

Keywords: Data physicalization, Embodiment, Situatedness, Interaction design

1. Introduction

In most instances of data physicalization, the needs are not met in those critical phases. The instances can display information in a clear and concise manner but for aesthetic and decoration purposes only. There is a critical theme that this article seeks to address. It is with how one can assist users in making a transition from a point where they can actually comprehend information to one where they can critically think and analyze information in relation to power. I think there is a need for a combination of two different aspects in this field. The aspects are those of embodiment and situatedness. There are instances like those in *Chemical in the Creek* [1] and *Torrent* [2] where both aspects are included in a project design. However, in my opinion, some designs are more focused on clarity and less on critical thinking. The article will cover how to incorporate both in a critical review.

I will reveal how each element works independently to trigger reflection, then demonstrate how their integration uniquely transforms users from understanding to questioning the power discourse structure behind it, and finally propose practical design principles for this key goal.

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DOI: 10.54254/2753-7064/2026.37031

2. Background: case analysis

Figure 1. Torrent.The muscle tension (EMG data) of the musicians is dynamically visualized through the intensity of water flow turbulence. Source: [2]

As shown in Figure 1, *Torrent* [2] places musicians around a shared water installation so that bodily effort, sound, and visible turbulence can be perceived simultaneously by performers and audiences. *Torrent* is an interactive music-making installation created by Aura Pon, Eric Pattison, Lawrence Fyfe, Laurie Radford, and Sheelagh Carpendale in 2017, presented at the Eleventh International Conference on Tangible, Embedded, and Embodied Interaction (TEI '17). The system enables musicians to manipulate water flow through their body movements, creating a direct connection between physical exertion and visual feedback.

The muscle tension (EMG data[1]) of the musicians is dynamically visualized through the intensity of water flow turbulence, the performers change the physical form of the data in real time through body movements.

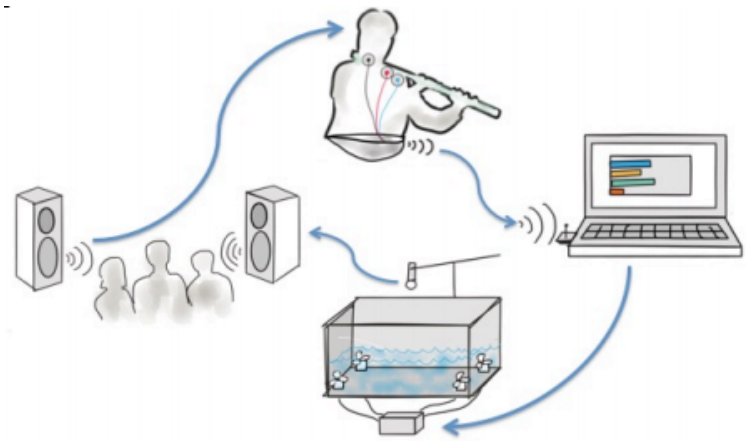

Figure 2. The torrent system, showing data flow. Source: [2]

[1] The installation captures electromyography (EMG) data from performers, measuring muscle electrical activity during perform. This biological signal drives real-time visualization through water turbulence intensity, with stronger muscle contractions producing more turbulent water flows. Performers can reshape the data representation by altering their physical movements, creating a dynamic interplay between body, technology, and audience perception [2].

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Figure 2 illustrates the *Torrent* system's data flow, in which performers' bodily input is captured and processed before controlling the water display and associated sound feedback. Musicians perceive "water flow in response to limb tension" during performance, and the audiences understand the "efforts to fight against the water flow" during the appreciation process, thus remembering the disaster of the Calgary flood in June 2013 and the flood fighting spirit of the citizens.

Figure 3. Pollution data lanterns deployed at the Chelsea River wharf. Source: [1]

As shown in Figure 3, the pollution-data lanterns are installed directly at the Chelsea River wharf, enabling participants to encounter environmental indicators at the site to which the data refer. *Chemicals in the Creek* [1] is a way to physically express data by transforming pollution data into lanterns installed at a Chelsea River dock. Citizens touch lanterns—color-coded for chemicals—directly at the pollution site, embodying data through tactile interaction while situating it in the environmental crisis context. This integration triggers community-driven actions, such as demanding corporate transparency, through immediate sensory confrontation with industrial harm.

Pollution data lanterns were deployed at the Chelsea River wharf. Citizens touched the lanterns (corresponding to the colors/textures of the chemical substances) at the pollution source site, directly associating "data symbols" with "environmental crises". These interactions may lead residents to question, for instance, "Why is my community bearing pollution due to industrial activity?"

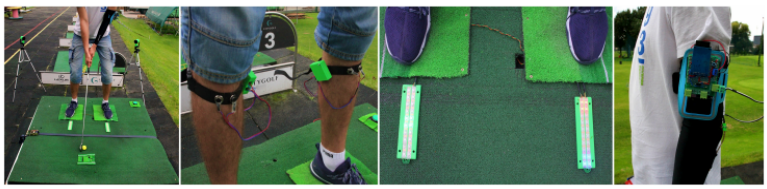

Figure 4. Subtletee device with vibration belts and pressure sensors. Source: [3]

Figure 4 shows the *Subtletee* [3] configuration, including vibration belts around the elbows and pressure-sensing footpads that detect and communicate deviations during a golf swing. *Subtletee* is a wearable training platform that targets new golf players to improve their swing positions through haptic feedback. The idea is to improve golfing skills while practicing through a tangible feedback experience that will guide players to better positions. The platform relies on vibration belts placed around players' elbows and pressure sensors in their footpads to identify inconsistencies in players' swing positions. Based on players' deviation from correct positions, a feedback response in vibration and pressure is provided to encourage players to make their first physical changes. New players modify their swing actions based on tangible feedback to initially "passively accept correction" to eventually "actively question their postures." *Subtletee* articulates how skills can be developed via embodiment.

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Figure 5. *Rain Interactive* installation with water-filled condoms. Source: [4]

As shown in Figure 5, *Rain Interactive* [4] suspends water-filled condoms as oversized "raindrops," inviting visitors to squeeze them and physically confront the contrast between pleasurable touch and the privatization of water. *Rain Interactive* translates water privatization into a tangible experience via water-filled condoms. The 'raindrops' are squeezed in the River Thames. The project conveys data through physical interaction and sets this within a contemporary context involving water rights. The reason this project is important is that the physical contradiction between a 'soft touch and a hard reality' triggers critical thinking regarding commodification.

Rain Interactive [4] transforms the abstract issue of water resources into a physical experience through the tactile interaction of water-filled condoms ("pleasant to touch and squeeze"). When users squeeze the "raindrops", they directly feel the physical existence (embodied nature) of water, which prompts reflection on the fact that "water, as the source of life, has been privatized". The designer emphasizes that condoms symbolize "preserving the source of life", and through tactile metaphor, reinforces the absurdity of the commercialization of water resources.

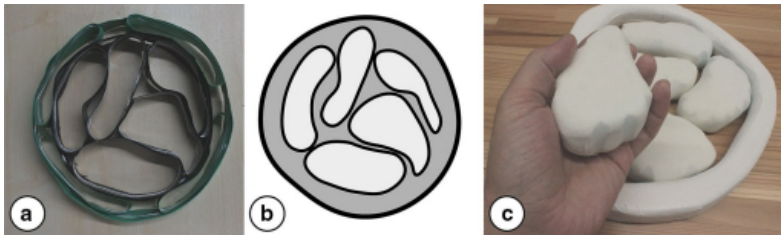

Figure 6. *Vital + Morph* shape-changing interface for remote monitoring. Source: [5]

Figure 6 presents the deformable Morph surface and movable Vitals modules, whose shape changes translate remote physiological signals into tangible and perceptible forms. *Vital + Morph* [5] is a shape-changing interface used for remote monitoring of patients' vital signs (such as heart rate and breathing), reflecting clinical data in real time through physical deformation. It consists of a deformable surface (Morph) and five self-propelled devices (Vitals).

It physically transforms vital sign data through material deformation (such as surface contraction or expansion), converting abstract signals (such as electrocardiogram waveforms) into tangible and perceptible shape changes. At the same time, it combines haptic feedback (such as force feedback)

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to allow users to directly "feel" the data flow and locate the data in daily life environments (such as home scenarios).

It proves that the physicalization of data can enhance emotional connection and situational awareness, making telemedicine data more intuitive and shareable, supporting my argument that physicalized data can break down the barriers of digital abstraction and promote natural human understanding and social interaction with sensitive information such as health data.

Figure 7. *We Harvest Wind* installation with spinning fans. Source: [6]

As shown in Figure 7, *We Harvest Wind* [6] centers on a suspended fan-based installation that visitors activate manually, converting bodily effort into light and making renewable-energy production experientially legible. In the artwork *We Harvest Wind*, visitors can activate the fans manually to convert wind energy into light energy, transforming the abstract concept of "green energy" into participation at the level of muscle memory. The artist pointed out: "Humans are the only species capable of converting wind into energy." Through physical operation, users can experience the energy conversion process firsthand, breaking the sense of distance towards renewable energy.

Figure 8 maps the design space of *Venous Materials* [7], including its fluidic architecture, flow and color primitives, deformation inputs, compositional strategies, and potential functional applications. *Venous Materials* is a new type of interactive material. It utilizes embedded fluid channels (such as micro-flow channels in PDMS[2]) to respond to physical deformations (such as pressure or bending), dynamically displays information through fluid flow and color changes, and realizes a battery-free self-contained interactive system.

It converts mechanical force data (such as pressure magnitude) into fluid flow and color mixing (such as irreversible color changes), represents the data dynamics within the material through geometric patterns (such as branches or grids), locates the data to everyday objects (such as shoe soles or keyboards), and turns intangible forces into visible physical feedback.

[2] Polydimethylsiloxane (PDMS) is a silicone-based elastomer widely used in microfluidics and soft robotics due to its unique material properties.

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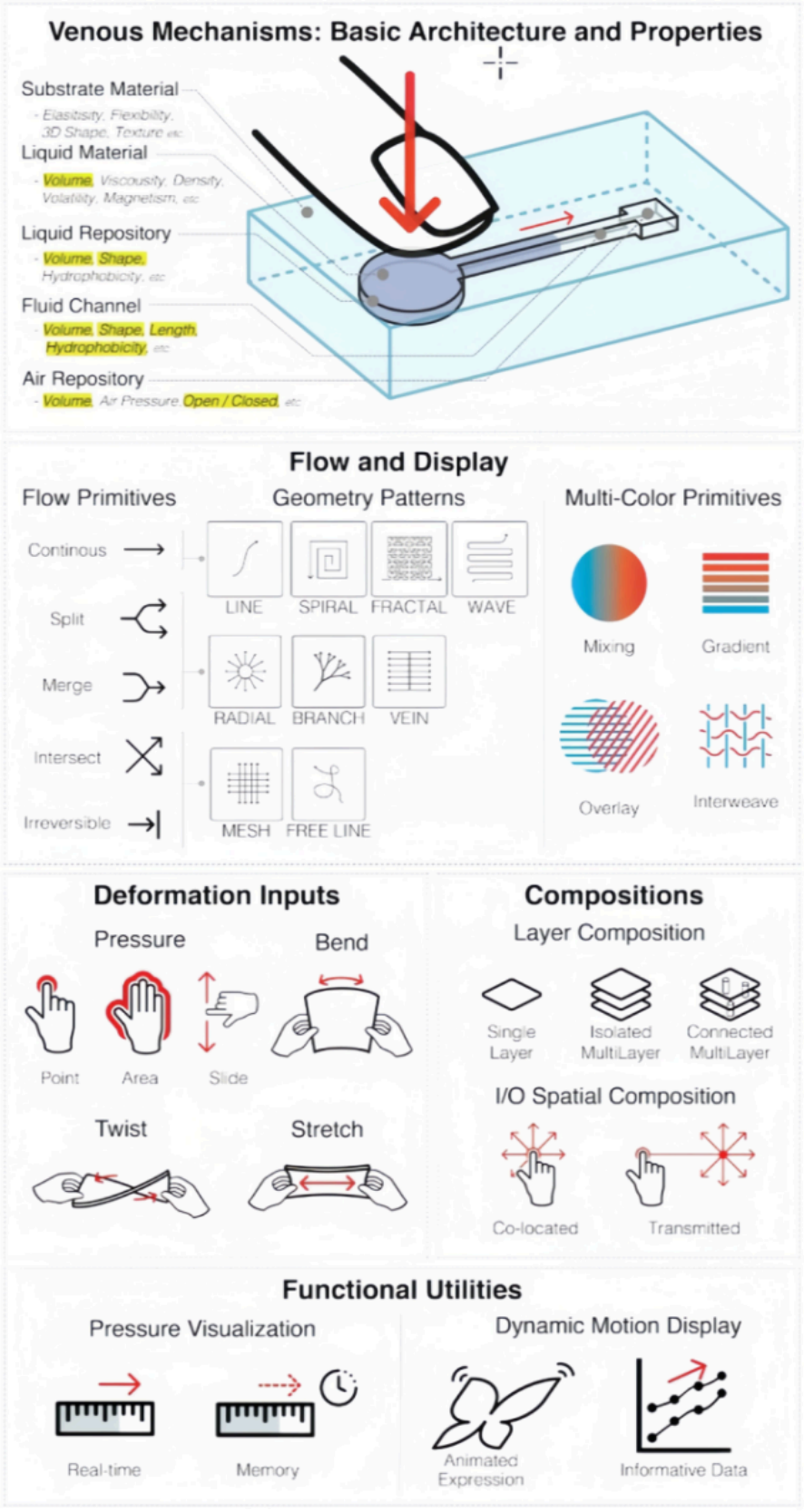

Figure 8. Design space of *Venous Materials*. Source: [7]

DOI: 10.54254/2753-7064/2026.37031

It shows the power of the material as an "intelligent medium" for interacting with data without using electronic components and supports my assertion that physical data has the power to break new ground in interaction design through passive materials.

3. The problem: clarity isn't enough for critical data

Data physicalization enables us to touch numbers that are purely abstract. However, when this is related to some wrong in the world—they manage water resources (*Rain Interactive* [4]), for instance, or bear the burden of climate change (*We Harvest Wind* [6])—simply knowing is not enough. We need to have critical thought stirred in us through designs. Sadly, research shows only about 38% [8][3]of physicalizations support even basic reflection, and far fewer spark true critique. *Vital + Morph* [5] is a case in point. It lets family members touch biometric data (like heart rate sculpted into forms) at home, embodying data through collaborative care discussions. But it avoids the tough questions about medical authority embedded in its forms, reinforcing healthcare power structures instead of challenging them. Similarly, the posture correction wearable device of *Subtletee* [3] operates in social isolation, enhancing the technology of specific movements without criticizing the broader social structure that defines the "ideal" movement. Although *Subtletee* effectively demonstrates the embodiment of skill acquisition, its focus only on corrective training standards within a single domain illustrates the limitations of non-political design: it assists the body to perform a specific task without further questioning who defines the standards of corrective training or how to innovate and update better forms of auxiliary standards. These projects show the gap: current designs aren't equipped to handle charged data where critical questioning is essential.

3.1. How embodiment makes data debatable

Embodiment turns data from a fact into an experience you can argue with. It does this through direct physical engagement that creates friction. Think about squeezing water-filled condoms in *Rain Interactive* [4]. The softness of the "raindrops" clashes sharply with the harsh reality of water privatization, forcing you to ask: who really controls this resource? Or spinning fans in *We Harvest Wind* [6]: just enough physical effort to make climate issues directly relevant and contentious. There is a set of projects that engineer irritation—pleasant touch meets unpleasant truth—to illuminate tensions between direct experience and systemic facts that are obscured in charts and figures. While *Vital + Morph* [5] provides positive touch for individual health needs, negative touch in *Rain Interactive* engages viewers with systemic water politics. The contrast between this and works like *Venous Materials* [7] is dramatic. There, viewers interact with biostreams through gestures in a lab. The effect is kinetically interesting but clinically sterile and lacking in social context. The lesson here is that successful embodiment relies on sensorimotor experiences to convert chart and figure facts into "contestaible truths" that entangle users within systematic concerns.

3.2. How situatedness makes data matter

Situatedness roots abstract numbers in places that give them meaning and urgency, thereby triggering collective debates. *Vital + Morph* [5] has turned the private body into a venue for ethical

[3] "While the data visualization community typically designs for exploration, we found reflection—the act of increasing one's self-knowledge—to be the most popular task physicalizations support (18/47) "[8, p. 5].

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discussion through health data that can be detected at home. The pollution indicators of the *Chemicals in the Creek* [1] project were directly placed in the polluted river, which prompted the community to take action against the polluters. The first two cases point out that situatedness applies to different scales: personal background (such as the *Subtletee* [3] worn every day) reveals how social norms shape individual behavior; Community environments (such as polluted streams) have turned global issues into local struggles; Cultural backgrounds (such as the *We Harvest Wind* [6] at the Stedelijk Museum in Amsterdam) elevate the debate to a more authoritative and public level. Embodiment enables data to be perceived (through squeezing and rotation), while the significance of situatedness lies in anchoring data to where the argument takes place. The work *We Harvest Wind* placed in the museum transforms abstract climate indicators into direct calls to action. In short, data gains moral weight through context.

4. Dynamic integration: shifting from comprehension to critique

But real magic happens when embodiment and situatedness interact. There is a feedback loop where concretizing nondirect observational data triggers people's response in other contexts and ignites a debate over broader philosophies. In *Rain Interactive* [4] project, people squeezed condoms in and around the River Thames because people need to "forcefully" confront the "undeniable" truth of water resource "privatization" and thus signed a petition. In *We Harvest Wind* [6], people with rotating fans placed the "remote" "energy responsibility" on users (their efforts=agency), but emissions "data" emanating from a neighboring "Polaris" business reveals a "hard truth"—the difference is meaningless [9]. In this museum context, people exposed "green washing" and are caught in a bitter debate between "corporate" and "consumer" responsibilities. Water is unfair through touch and chemicals in streamways make "pollutions" substantial. In *Torrent* [2], people are turned from data observers to activists through a collaborative performance where users' muscle tensions are translated through "four performers'" efforts through sensors to translate "the actual water currents and sounds" in a shared water reservoir.

The audience perceives the dynamic interaction between physical exertion and artistic expression through visual and auditory cues. The "seamless integration" of the system transforms physiological data into specific artistic experiences. Collective water operation metaphorically symbolizes the unified contribution of individuals and embodies the spirit of community unity that overcomes adversity with technology. *Chemicals in the Creek* [1] combines polluted water with the shock of the landfill itself. This integration creates "productive friction": the physical experience challenges the situation, and the situation reconstructs the physical experience, turning every interaction into a citizen's interrogation.

5. Design principles for critical integration

Cases like *Rain Interactive* [4] and *Chemicals in the Creek* [1] show that the key to making physicalization effective lies not only in tactile engagement or contextual placement. *Torrent* [2] further demonstrates how specific forms of interaction in the performance environment can reveal the hidden processes of musical expression, showing the combination of physical effort and context, thereby promoting public memory, while *We Harvest Wind* [6] uses participatory energy conversion to question the differences between individuals and enterprises in terms of climate responsibility.

Vital + Morph [5] and *Subtletee* [3], while limited in their significance, still point out that concretization enables personal meaning to be given to abstract information. The common factor in all of these examples is that in none of them is one aspect considered to the exclusion of the others.

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On the contrary, it is through the integration of physical and meaningful aspects that their potential for engaging people in critical thinking is realized. Therefore, how designers achieve this successful integration that is potentially capable of engaging users in critical thinking is summarized in the following key takeaways:

1. Contrast comfort and criticism. Put pleasurable facts side by side with unpleasant facts. The strategy employed by *Rain Interactive* [4] is to juxtapose the soft water balls with the hard reality of privatization. Such a clash can sometimes raise doubts in a person's mind and hence needs to be resolved by probing into the system.

2. Go to the site of contention. Implement physicalization on a site where an argument has already boiled over. In this case, place *Chemicals in the Creek* [1] on a contaminated wharf. This is to tap into this existing community power that converts impact into action.

3. Expression and power through form. The aesthetic contrast between beauty and power is employed to expose concealed creative processes. The beauty of water flow represents power in an aesthetic way as it engages viewers in a creative process expressed through music.

6. Conclusion

Achieving a combination between physical interaction and meaningful situatedness changes the face of data physicalization. It is a shift from passive understanding to critical and active engagement within and with the power structure. Projects like *Rain Interactive* [4], *We Harvest Wind* [6] and *Torrent* [2] illustrate that while each one is worth a small value in its own right, it is a uniquely valuable experience when all are coupled together. It reveals a hidden hierarchy – whether in art through its physical manifestation or in sustainable development through shifting responsibilities – and changes the landscape of data representation into a critical site for dialogue. The impact of this is not to be underestimated in a world where artists and designers work in a democratization of information that is dominated by large amounts of data. The integration is not for information display alone but to provide tools for empowering society. So, how can we further promote these principles to address more complex and urgent social challenges?

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