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RESEARCH ARTICLE

Equilibrium as the common ground: Introducing embodied perception into structural design with graphic statics

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Abstract The analogy between the human body and architectural structures dates all the way back to ancient times and has significantly shaped the design of buildings and structures. The article examines the body's historical influence on how structures are perceived and designed, demonstrating how the body shapes the "technical truth" dimension of structural design while oblivious to the importance of an "artistic truth" or perceptual dimension. This article aims to connect recent neuroscience findings and their implications for structural design through graphic statics and its design methods. Finally, this article proposes an equilibrium-based structural design approach for designing embodied structures based on graphic statics.

1. Introduction: the body in structural design

Comparisons between buildings and the human body have a long history and have become more prevalent in architectural theory and practice since the Renaissance. For example, Leon Battista Alberti describes the art of building using the metaphor of bones, muscles, ligaments, and skin (Alberti, 1988). The analogy between body and structure was frequently mentioned in construction and architecture research, particularly during the nineteenth century, as building science developed. Among them, Thomas Tredgold compared structure and construction to architecture's anatomy in his study of the science of the human body, arguing that the concept of the body and its parts as well as the mechanisms that govern its various behaviors, are

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strikingly similar to architecture as a whole in terms of its constituent parts and material structure (Tredgold, 1820). This fundamental and critical criterion is frequently overlooked during the architect's design process, leaving the structure solely in the hands of the structural engineer—leaving the architectural structure as a purely intellectual activity rather than derived from any particular bodily experience, effectively suffocating the bodily meaning of structure (Picon, 2005).

Fortunately, a group of architects and structural engineers have constantly incorporated the human dimension into the process of structural design and thought by drawing inspiration from or imitating the body and experience. To reintroduce the human dimension into structural design and thought, this article reviewed various historical uses and conceptions of the body in structural design and extended them to include recent neuroscience findings regarding embodiment and its relationship to structural perception. Based on the critical role of equilibrium in the embodiment, the following paper will review and analyze various embodied structures from selected architectural examples to propose an equilibrium-based structural design approach for designing the embodied structures based on graphic statics.

2. Anatomical perspective

As early as the 15th century, Leonardo da Vinci used the diagram of the human spine in *Codex Atlanticus* to describe the logic of the supporting structure of the dome. In the nineteenth century, Viollet-le-Duc's research on Gothic churches expanded this anatomical analogy between body and structure. Influenced by the comparative anatomy of French paleontologist Georges Cuvier, Viollet-le-Duc used anatomy as an analytical method to study the relationship between structure, function, and form in the Gothic church. Cuvier's comparative anatomy began by examining how the organs of an organism work together to form a unified whole, both formally and functionally. Inspired by Cuvier, Viollet-le-Duc used graphical representation methods such as exploded diagrams and sections to reveal the inextricable relationships between each structural element in the Gothic church as well as the synergistic relationships and mechanics that underpin their organization (Viollet-le-Duc, 1990). Thus, Viollet-le-Duc argues that the form of architecture is determined by structural principles, such as organic and rational nature; once structural and construction principles are established, the form or "style" will naturally follow (Viollet-le-Duc, 1854—1868). Similar to the exploded view used to dissect the human body, Viollet-le-Duc used it to disassemble the structural elements of Gothic churches, demonstrating clearly and visually the static relationships between the parts and the steps involved in how the ribs, for example, transferred the stress from the vault to the flying buttress below (Fitchen, 1981) (Fig. 1). This anatomical representation of the structural system demonstrates unequivocally that the organic structural system of Gothic architecture is derived primarily from force equilibrium, as a result of the mutual

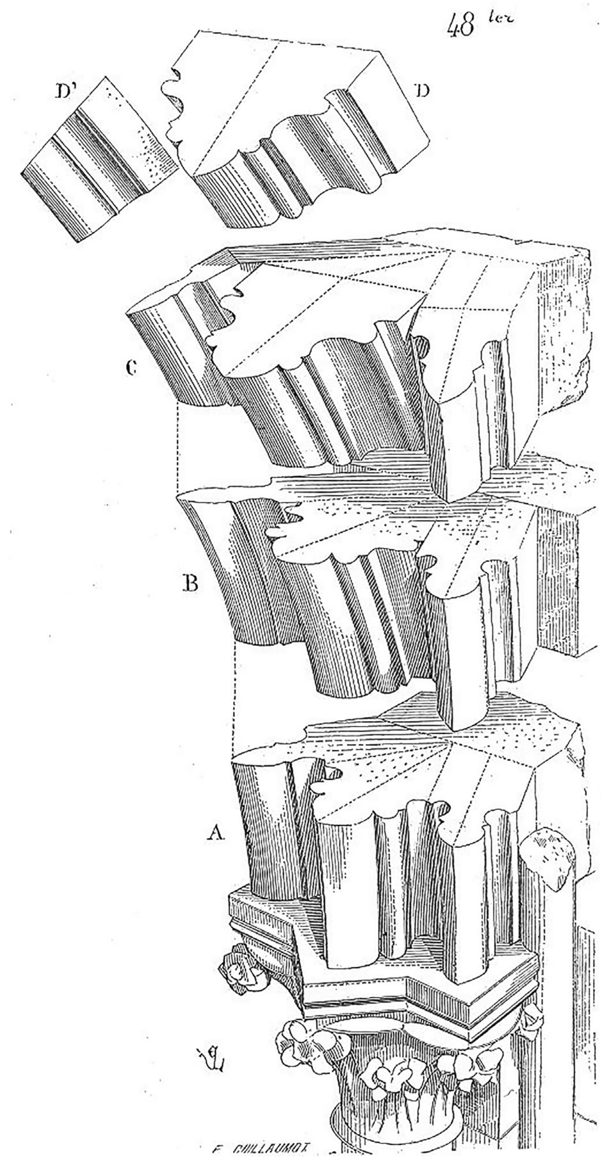

Fig. 1 Exploded drawing of the Gothic arch. Source: from "Dictionnaire" (Viollet-le-Duc, 1854-1868) by Viollet-le-Duc, "Construction," volume 4; public domain.

counteraction and overall equilibrium of the forces acting and reacting between the elements, thus "each stone with a function such that no stone could be removed without compromising the entire structure" (Viollet-le-Duc, 1990, pp. 259—260). Furthermore, Viollet-le-Duc views this diagrammatic representation of equilibrium condition not only as an interpretation or reproduction of current architectural styles but also as a tool to rationally stimulate the "active imagination" (Viollet-le-Duc, 1987). Compared with the *Beaux-Art* system, which was dominated by passive memory, this active anatomical graphic perspective is a more rational and scientific method of conveying and even manipulating knowledge. This abstract representation not only assists the viewer in comprehending and absorbing the structural principles underlying the optical forms but also guiding the viewer in refining and reconstructing knowledge, which is necessary for progressing toward an analytical memory and even creating a new "style" (Vinegar, 1995).

As a continuation of Viollet-le-Duc's rational investigation of the body and structure, in 1866, under the influence of the anatomist Georg Hermann von Meyer, Karl Culmann described a vector-based graphical structural design methodology on the basis of the equilibrium condition of tension and compression curves to represent the inner stress condition in load-bearing structures in his book, *Die graphische Statik* (Graphic statics) (Maurer, 1998). Culmann used graphic statics to analyze the stress patterns in curved structures such as the Fairbairn crane and discovered that they are remarkably similar to the internal structural patterns of the proximal femur drawn by von Myer in 1867 (von Meyer, 1867) (Fig. 2). The Berlin surgeon Julius Wolff confirmed this similarity in 1870 after photographing the internal structure of the sliced bone (Moravánszky, 2019). These remarkable investigations exemplify Viollet-le-Duc's anatomical perspective on the rational relationship between form and structure. Thus, the way nature constructs the skeleton and the human body is highly consistent with the logic and purpose of structural design.

Culmann's student, Maurice Koechlin, sketched the steel structure of Eiffel Tower at Gustave Eiffel's firm under the influence of graphic statics. However, this result of utilizing the fewest possible materials to achieve the most efficient structural design was widely discussed at the time. On the one hand, people were impressed by the new forms created by the new materials but were scandalized by the fact that the "fleshless" or "massless" structural skeleton did not meet the project's artistic and aesthetic requirements: "... the human skeleton is surely the most perfect work of engineering. But for my eye, when it is in search of beauty, it is the blooming flesh that is decisive" (Lux, 1910, pp. 3–4). Although the design of the Eiffel Tower exemplifies Viollet-le-Duc's rationality that form follows structure, these arguments also demonstrate the omission of other systems such as muscle and skin from the analogy between structure and the human body, resulting in a visual imbalance in the skeleton—the experience and aesthetics of the body as a whole cannot be seen separately. This idea indicates that focusing exclusively on structural techniques precludes structural design from an active comprehensive shaping of architectural space.

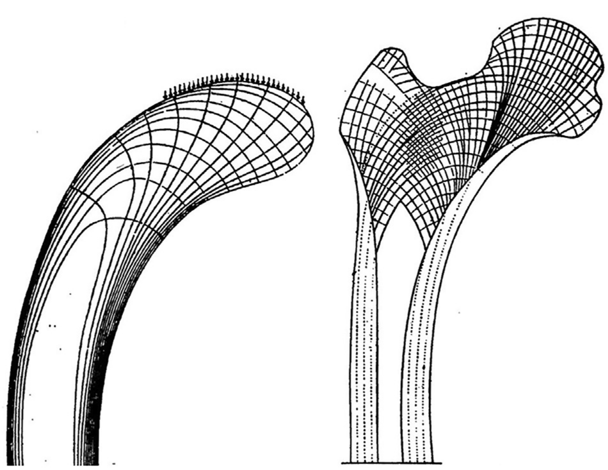

Fig. 2 Left is Culmann's analysis of the patterns of internal forces in a Fairbairn crane by graphic statics; Right is Julius Wolff's drawing of trabecular structure in the proximal femur. Source: from "On Growth and Form" (Thompson, 1942) by D'Arcy Thompson; public domain.

3. Ontology and representation of the structure

The debate over the Eiffel Tower's "bone" and "flesh" dates all the way back to Karl Bötticher's discussion of the art-form and core-from of structure. Even before Viollet-le-Duc, the German theorist Karl Bötticher was concerned with the representational aspect of Greek architecture and the ontological aspect of Gothic architecture (Frampton, 1995). In his book, *Die Tektonik der Hellenen*, he coined the German terms, *Kernform* (core-form) and *Kunstform* (art-form), as analytical tools for interpreting the structural design. Both of these terms "associate the separation between static structures from its artistic apparel (Mayer, 2004, p. 18)." The *core-form* refers to an architectural element's material and static function, while the art-form is designated as how this static function becomes apparent and acquires meaning. Bötticher sees the relationship between *Kernform* and *Kunstform* in architectural structures as a kind of corpus or *Körper bilden*, arguing that architecture should focus on the appropriate interconnection of structural elements to generate an expressive *Kunstform* through the construction of *Kernform* (Schwarzer, 1993).

Similar to Bötticher, Gottfried Semper argued that Viollet-le-Duc's theory constrained artistic freedom and imagination and expanded his famous *Raiment theory*, which divides the structure into scaffolding and cladding respectively; these two correspond to the ontology and representation of the structure (Gottfried, 1989) (Oechslin, 2002). However, Semper's view was later criticized by people such as Hendrik Petrus Berlage, Otto Wagner, and August Schmarsow, who argued that the two should not be studied separately, and that the internal skeleton must be considered alongside its ornamental artistic expression to return to the inseparable "full-body" (Berlage, 1905, p. 24) (Frampton, 1995, p. 89). The Viollet-le-Duc's limitation is that he considers the *Kunstform* of the structure as a natural consequence of the *Kernform*, starting only at the level of construction and technology. While Semper's Raiment theory transitionally emphasizes the representational dimension of ornament, it obliterates its technical part. Similar to how the bones and the skin of the body are inextricably linked, the relationship between *Kunstform* and *Kernform* should be complementary rather than dichotomous. In this regard, Fritz Schumacher proposed the "double truth concept," in which "technical truth" serves as the foundation for the realization of "artistic truth;" additionally, "artistic truth" serves as an enhancement or symbolic representation of "technical truth" (Schumacher, 1838, p. 228) (Moravánszky, 2019).

Viollet-le-Duc et al. have conducted many scientific studies on the "technical truth" of the structure of the Medieval Church through anatomical representation.

Similarly, since the 19th century, long-time scientific interests and debates have existed regarding the "artistic truth" of structural design.[1] One of the most representative figures is Heinrich Wölfflin. In his study of "force" in Renaissance and Baroque architecture, Wölfflin focuses not so much on the building statics but rather on how the body has been used as a "metaphor of force" to empirically "feel" the psychological tension and compression (Wölfflin, 1994) (Forty, 2000). He reveals that the "force" of structure exists not only on a physical level but also on a psychological level through *Einfühlung* (empathy) brought about by embodiment. Empathy explains the capacity to understand and "feel into" other things through the sympathetic projection of the human body. It primarily explains the unified human perception of structural expression. The study of empathy on how humans psychologically and biologically perceive the expression of structures through the human body has been addressed in numerous architectural designs and research throughout history.[2] However, since the early twentieth century, the theory of empathy has been primarily driven by technology-oriented formalism. Further developing the "artistic truth" part of structural design was restricted by a lack of scientific basis to explain or demonstrate the principles underlying how humans read and resonate with structural expressions (Mallgrave, 2013). Therefore, it cannot provide detailed guidance for the structural design.

4. Neuroscientific approach

Recent rapid advances in the field of *Cognitive Neuroscience* enable a new way of scientifically conceptualizing the metaphor and analogy between structural design and the human body; it also expands our theoretical framework through the notion of embodiment and embodied simulation derived from theories such as empathy, thus marking the beginning of a new chapter in the history of the body in structural design (Mallgrave, 2013). With the goal of investigating representational and artistic mechanisms of perception, cognitive neuroscience provides an egocentric perspective on human perception and understanding of structures (Freedberg and Gallese, 2007). Similar to how the development of biological sciences has inspired and promoted structural design and thinking throughout history, the findings from neuroscience can provide a rigorous explanation of the human embodied perception of structural expression, which complements the research on the representational aspect of structural design.

As a milestone in neuroscience, the discovery of the *Mirror neuron* in the mid-1990s established that the neural circuits used to simulate other people's actions are located in the same areas of the brain as those used to perform our own actions (Rizzolatti et al., 2006). Thus, traditional psychology and cognitive science's perception principles, which consider perception as a computer-like processor of visual signals in the brain, are flawed—this passive and disembodied dualistic view of human perception is one-sided (Pérez-Gómez, 2015). According to the mirror neuron, the same neural structures involved in our own bodily experiences contribute to conceptualizing what we see and feel in the world (Ebisch et al., 2008). This embodied perception process is based on the mechanism by which humans initiate unconscious perception (System I) prior to consciously analyzing it (Kahneman, 2011)—embodied perception does not begin with a specific and precise analysis. It is a precognitive or pre-reflective instant perception occurring prior to conscious awareness and is evocative of a previous similar bodily experience (Gallese and Gattara, 2015, p. 162). Therefore, the mirror perception system is "a direct form of 'experiential understanding' of others, achieved by modelling their behaviours as intentional experiences, based on the equivalence between what the others do and feel and what we do and feel" (Gallese, 2007). This idea implies that human body is necessary for us to have an empathic relationship with the world (Rizzolatti et al., 2006). Thus, when individuals observe a gesture that resembles a previous bodily memory, they directly and unconsciously evoke the previous bodily experience and mood associated with this bodily gesture, thereby demonstrating their ability to read into things. This phenomenon may account for the perceptual similarity between the structural designer and an untrained observer—their initial unconscious reaction to the same structural expression will be very similar due to their nearly identical bodies. Following the unconscious impression, the structural engineer's knowledge as well as the knowledge of other individuals with varying educational/psychological backgrounds and cultural sensibilities, will manifest in the conscious and analytical reading of the structural expression. On the basis of the mirror neuron, the notion of "embodied simulation" was proposed as an extension to explain how humans not only "see" the built environment but also feel and simulate emotions and actions from the world through the medium of the body and experience (Gallese, 2007) (Thompson, 2007). This idea is similar to Merleau-Ponty's view that "the body is the vehicle of being in the world (Merleau-Ponty, 1962)." The findings of the embodied simulation were based on the premise that perception and cognition are intrinsically dependent on the organisms' interaction with their environment (Varela et al., 1991) (Thompson, 2007) (Jelic et al., 2016). Which meanings, other than the mirrored projection of a static bodily gesture, embodied perception could simultaneously emerge from active dynamic action and movement. The recent research indicates that our embodied simulation is not limited to the social world. Humans possess the "precognitive capacity to mirror the tactile values of all objects or forms in our environments,

[1] See for example M. Merleau-Ponty, Phenomenology of Perception, London: Routledge and Kegan Paul, 1962; H. Wölfflin, "Prolegomena to a Psychology of Architecture," in Empathy, Form, and Space: Problems in German Aesthetics, 1873–1893, Santa Monica, Getty Center Publication Programs, 1994; K. Frampton, Studies in Tectonic Culture: The Poetics of Construction in Nineteenth and Twentieth Century Architecture, Cambridge, Massachusetts: MIT Press, 1995 (2001).

[2] See for example Schmarsow, August. Das Wesen Der Architektonischen Schöpfung: Antrittsvorlesung Gehalten in Der Aula Der K. Universität Leipzig Am 8. November 1893. Leipzig: Karl W. Hiersemann, 1894; S. Holl, J. Pallasmaa and A. P. Gómez, Questions of perception: phenomenology of architecture, SanFrancisco,CA: William Stout Publishers, 2006.

both living and non-living" (Mallgrave, 2015). Vittorio Gallese, a co-discoverer of mirror neurons, also proposes that embodied simulation be used in place of the traditional term "empathy" (Mallgrave, 2015).

The embodied simulation shows that our ability to read force, balance, and aesthetics of structures is dependent on our bodily memory. It is the sensation of muscular contraction during the gesture that is memorized as well as the position of the limbs in relation to one another and the body as a whole. Thus, bodily gestures and movement patterns can serve as a reference for designing structural expressions. Whether it induces or inhibits the perception of the built environment, one could argue that the fundamental goal of all design thinking is to establish an aspirational dialogue between the human body and architectural space, thereby enhancing the interconnectedness and balance of matter and space (Jelić, 2015) (Drake, 2005). The mechanism by which spatial order is established through motion and embodied experience of spatial structure is linked to *proprioception* and *bodily schema* in neuroscience.

Proprioception is the ability to grasp one's own position in space, including limb sensations, movement in space, and sense of effort (Charlton, 1888) (Goodwin et al., 1972). They helped develop the human balance system, along with vestibular sense and kinesthesia. In addition, proprioception is the study of how the body's parts unconsciously coordinate with one another to maintain flexible balance and gesture and how the body as a whole coordinates with its surrounding space to maintain balance in space, whether static or moving (Angelaki and Cullen, 2008). The embodied sense of balance was defined by the sense of force generated by the body in response to sensory signals from muscles, joints, and skin receptors in response to stretch and compression of body tissues (Colombo et al., 2018). The notion of *bodily schema*[3] is a representation of this constantly changing muscle configuration that unconsciously controls our body's shape and posture, our actions, and our movement in space (Jelic et al., 2016). Notably, interoceptive emotional inputs in the form of motivating tendencies to act are included in body schemas on the bases of balance (Gallagher and Bower, 2014). Accordingly, it represents both physical and psychological equilibria.

These findings from cognitive neuroscience corroborate, on the one hand, the scientific rationale behind Viollet-le-Duc and Wölfflin's hypothesis that the body serves as a "metaphor of force" for reading and perceiving the logic of forces behind structures; on the other hand, they also fill in a gap in their empirical findings on people's perception of structures: the influence of dynamic interaction on the body's relative relationship to the built environment. Suppose we interpret Viollet-le-Duc's analogy between the composition of structural elements and the composition of body parts in medieval churches through diagrams such as exploded drawings or sections through the lens of embodied simulation and proprioception. This diagrammatic representation aids the viewer in comprehending the relationship between forces and equilibrium because people were "rendering" and simulating the observed structural composition using their muscle memory of the body parts, thereby revealing the sense of "force" behind it. Additionally, one can gain a better understanding of the purpose of structural expression in Gothic churches as described by Nikolaus Pevsner, which is "to enliven inert masses of masonry, to quicken spatial motion, to reduce a building to a seeming system of innervated lines of action" (Pevsner, 1943, p. 90), that is, to stimulate bodily movement and interaction with the structure of the building.

5. Equilibrium as the common ground

Considering that structural design encompasses both technical and artistic aspects, using the body as a design reference or method should be analogous to both the physical and psychological balance of the structure's bones and muscles. Otherwise, the structural significance of architectural space cannot be fully expressed. Consequently, balance is a critical reference point and tool in architectural and structural design. For instance, balance is a recurring theme in a number of Auguste Choisy's works. As with Viollet-le-Duc, Choisy's anatomical interpretation of architectural structure implies that balance is a structural strategy as well as an aesthetic principle. Accordingly, Choisy frequently begins his designs by addressing the aesthetic feature of balance before moving on to structural form (Etlin, 2010).

Cognitive neuroscience demonstrates that what enables us to comprehend the balance of "forces" is not only the formal relativity of the medieval church's structural elements as described by Wölfflin but also the dynamic balance between our bodies and the structure. The latter's reference system encompasses the relationship between one's limbs and the relationship between the person and the structural elements that surround it. This aspect is the critical factor in dynamic interaction with structures, as it results in the perception of equilibrium as described in the embodied simulation rather than simply the projection of "force" by the body's geometric relations. Therefore, the influence of the structure on balance and bodily schema which can alter one's perception of and emotional response to the building is twofold. First, structural forms imply a state of balance in body posture. Second, structural form implies the tendency and manner of interaction and movement (position, orientation, scale) in relation to the body in which it is placed. The former is analogous to implying the muscular sensations of a body in fragile balance or out of balance in a frame in the bodily schema series of motions (Fig. 3). By contrast, the latter is intended to influence the possibilities of interaction with the body through the structure's relationship to the body (Fig. 4). Both intend to stimulate the arousal of different bodily schemas in people's experiences through the design of structural balance.

In particular, the dynamic interaction with structures is not limited to the body's action because the structure is static. Moreover, predicting the person's relative orientation, the field of view, and velocity in relation to the structure is difficult. Apart from direct stimulation of the

[3] For other details about bodily schema, see Cuzzolaro, Massimo. Body Schema and Body Image: History and Controversies. In: Cuzzolaro M., Fassino S. (eds) *Body Image, Eating, and Weight*. 2018, Springer, Cham, pp. 1—24.

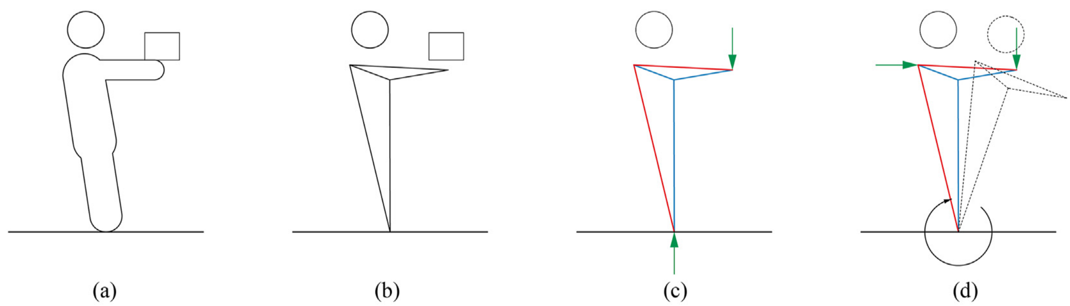

Fig. 3 Bodily schema of carrying a load in (a) and its graphical representation (b), which is similar to the graphics statics' force flow in (c), and the tendency to lose balance when adding even a small horizontal force in (d), therefore expressing the fragile bodily balance behind this schema.

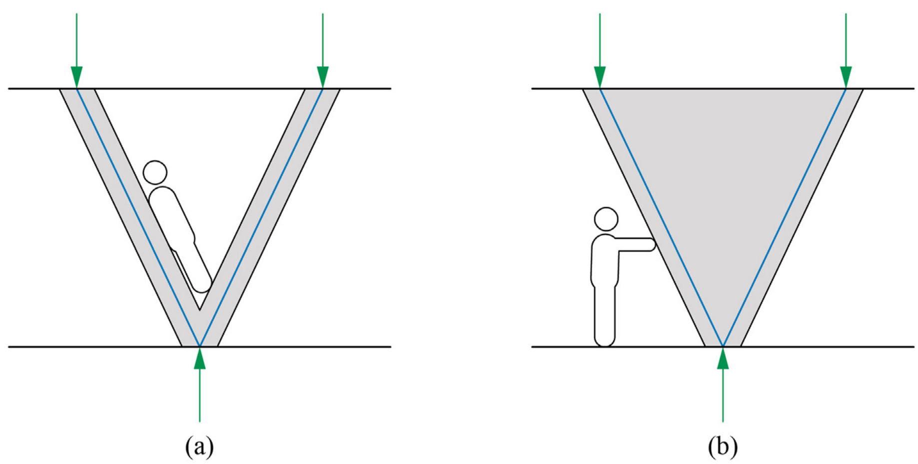

Fig. 4 Different structural representations could influence different body interactions, thus arouse different embodied perceptions.

movement, the primary way structural design can convey the perception of "force" rather than purely physical displacement—a concept coined by Rudolf von Laban as "impulse or effort"—through the expression of dynamic bodily action (Arnheim, 1974, p. 408).[4] In neuroscience, this manifestation of force that results in a movement or the proclivity to move is referred to the term *enactive*, and it is the primary trigger for body movement and perception.[5] By incorporating "Immobile Motion" between the structure and the person—an invisible psychological effect of the "tension" between us and the structural elements—static structures can still create "Directed Tension" within them (Arnheim, 1974).[6] Recent research has even demonstrated that people experience more kinetic sensations when confronted with implied motion than when confronted with less dynamic actions (Proverbio et al., 2009).

More importantly, the structure should transition from introspective to more compatible structural design on the basis of the body's physical and psychological characteristics. Similar to Viollet-le-Duc, the equilibrium system of great Gothic architecture is honored by distinguishing between Roman structures' "inertia" and Gothic structures' "active" principle (Viollet-le-Duc, 1863, p. 270). By proactively designing a pre-reflective structure, the structure enables a more interactive spatial experience while carrying loads. This active design of structural expression is comparable to what Arnheim refers to as the Acropolis's column perception: we perceive the column as standing upright and bearing the weight of the roof not only because we project ourselves onto it but also because the column's relative position, proportion, and shape enable and compel

[4] Rudolf von Laban distinguishes between body displacement and the visual expression obtained from body dynamic action through the study of dance. Although he thinks that the body displacement is defined simply by the attributes of physical vectors, the expression of human motor behavior concerns the impulse that gives rise to the movement.

[5] Varela et al. argue that our perception arises from interactions with the surrounding environment, accomplished in an active and dynamic relationship. To study the generation of this embodied view of mind, they stablished the enactive approach; the term enactive depicts a concept that "a living being is an autonomous agent that actively generates and maintains its own cognitive domain through continuous reciprocal interactions of the brain, body, and the world." For other details, see F. J. Varela, E. Thompson and E. Rosch, *The Embodied Mind: Cognitive Science and Human Experience*, Cambridge: The MIT Press, 1991.

[6] Arnheim's account of "Immobile Motion" emphasizes visual perception and is dismissive of bodily perception, whereas neuroscience demonstrates that the body plays a significant role in his description of people's perception of "tension."

us to do so. Conversely, a poorly designed structure will not resonate with us (Arnheim, 1974). Then, the question is, which specific operational tools should be used to design structures that actively incorporate physical—psychological equilibrium?

As demonstrated by Viollet-le-Duc, the exploded diagram graphically illustrates the forces acting on the structure by emphasizing the organic connections between adjacent parts. Furthermore, the exploded diagram can be used to guide participatory cognitive behavior of forces within the structure by re-enacting how the ribs transfer pressure from the vault to the flying buttress in consciousness via psychological equilibrium (Fitchen, 1981, pp. 75—77). By contrast, the exploded diagram is merely a disassembly and interpretation of a pre-existing structural system. It is incapable of serving as a medium for the design process, which is about operation and transformation. It is comparable to finite element analysis (FEM), which is widely used in structural design today to analyze the structural system rather than to facilitate continuous deformation or iterative design operations (Kotnik & DAcunto, 2013). In comparison, Maurice Koechlin's graphic statics approach to designing the static system for the Eiffel Tower provides significant advantages and the ability for diagrammatic manipulation.

Graphic statics is a vector-based construction of the equilibrium condition.[7] It has already been formalized as a methodology for designing building structures by Karl Culmann (Maurer, 1998). It is a simplified, abstract, and graphical representation of forces equilibrium that is fundamentally different from mathematical structural analysis and calculations. It is practically the resultants of stress fields in structural materials—a spatial network composed of compression and tension forces in equilibrium, also known as force flows (Muttoni et al., 1997).

Several books introducing graphic statics or structural design all explain equilibrium through the use of force flows and human body motions[8] (Fig. 5). Predictably, the mirror neuron enables people to easily comprehend the tension and compression involved in bodily motions because we share nearly the same equilibrium experience with our bodies and develop empathy for these forces in response to a specific bodily gesture (Vignemont, 2010). "Architectural design is the specialisation of a balanced bodily tension so that, while moving, the body maintains this equilibrium (Ionescu, 2016)." As pointed out in mirror neuron, our conceptualization of things begins in the unconscious, through the evocation of pre-existing experiences. In addition, we are all born experts in equilibrium; our bodies' experiences have prepared and accumulated an infinite variety of muscle memory in the bodily schema and associated emotions. This equilibrium experience, which is stored in each body, can be used as an already prepared vocabulary in the design of abstract equilibrium systems by graphic statics.

As previously stated, proprioception is the sensation of tension and compression forces applied to our muscles, joints, and skin. This definition is consistent with the graphic nature of force flows based on compression and tension in graphic statics, allowing for a visual and straightforward interpretation of bodily experiences as equilibrium of abstract compression and tension forces (Fig. 6). Thus, the equilibrium diagram—a graphic representation of force flows—can integrate human embodied perception and structural design. Graphic statics is not only the logic for achieving physical structural equilibrium but also the principle that guides the design of architectural geometries and geometric compositions with the potential to emotionally project bodily experience.

For example, the force flow in Fig. 3(c) can be used to describe the bodily equilibrium condition and muscle stresses in Fig. 3(a) and the feeling of possible momentum in Fig. 3(d) when subjected to horizontal forces. Using the body schema as a guide, graphic statics can use force flow distribution as core-form to design structures. By composing and deforming graphic statics, we can directly guide the conceptual design of core-form, guiding the conceptualization of the holistic conceptual structure model. Moreover, our body experience has muscle memory and an emotional memory associated with these gestures. Therefore, when we use the experience of body balance to guide the design of structural equilibrium, we include both the physical and psychological aspects of balance, which contain people's emotions. For example, the entangled relationship between bone and flesh in the Eiffel Tower can be reconciled by balancing physical force flow with psychological perception.

Intuitive thinking informed by bodily experience is critical during the conceptual design phase, when architects collaborate to quickly outline the composition and thinking behind the building's overall structural and spatial concept. Given that the conceptual structural design phase excludes detailed structural analysis and verification, considering its overall structural logic is more critical. Moreover, this embodied structural design approach allows for incorporating human body experience into the process of designing equilibrium, adding a dimension of perception and experience to the structural design and allowing the structure to define the expression of space better. Many projects by Santiago Calatrava are the illustration of this structural thinking. He was inspired by analogies and metaphors for bodily gestures, incorporating them into the structural design process to achieve expressive structural tension.[9]

[7] The exploration of equilibrium in graphic statics is based on the simultaneous use of location plan (form diagram) and force plan (force diagram). While the location plan depicts the geometrical equilibrium condition, the force plan depicts the magnitude of the individual forces. The application and operation of graphic statics discussed in this paper focus on the graphical representation of the structures in relation to embodiment under the use of form diagrams in the conceptual design phase. Therefore, the force diagram, which is more critical for structural analysis and calculation, receives less attention in this paper.

[8] See for example recent textbooks on structural design such as Allen, E. & Zalewski, W.: Form and Forces: Designing Efficient, Expressive Structures, Wiley, 2009, Muttoni, A.: The Art of Structures: Introduction to the Functioning of Structures in Architecture, EPFL Press, 2011.s.

[9] See for example from many of his drawing on the analogue between body and structure in C. Politakis, *Architectural Colossi and the Human Body: Buildings and Metaphors*, New York: Routledge, 2018; Calatrava, Santiago, and de A. C. Carrillo. *Santiago Calatrava: Drawing, Building, Reflecting*, 2018.

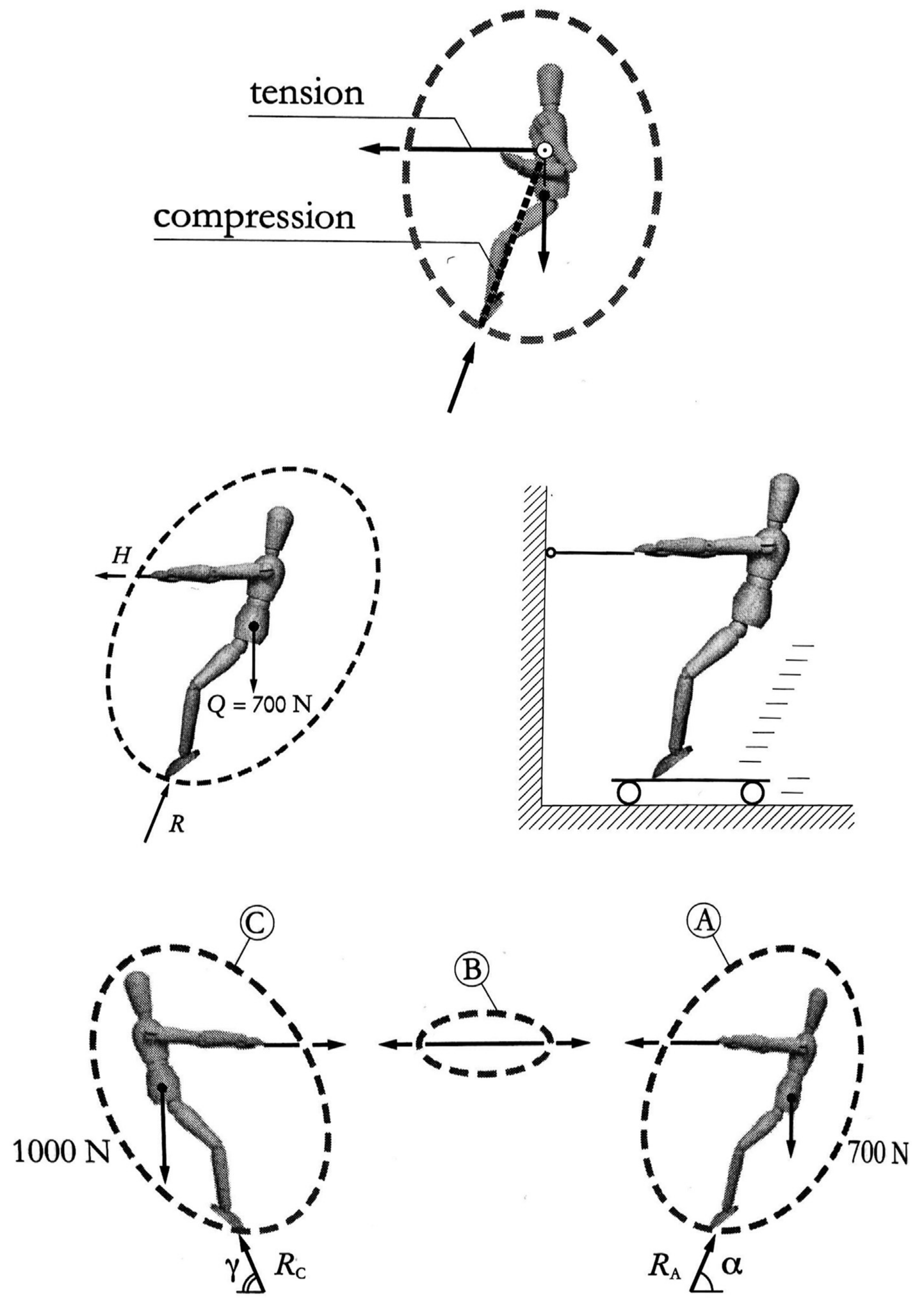

Fig. 5 Human bodies are used to describe different forces and equilibrium in graphic statics. From "The Art of Structures: Introduction to the Functioning of Structures in Architecture" (Muttoni, 2011) by Aurelio Muttoni.

More importantly, the force flows in graphic statics serve as more than a simplified method of modelling structure. It also has the potential for operability. Graphic statics not only can visualize and diagrammatize the abstract equilibrium relationships of structures during the design process but also that "the reduction to the simple concept of vectorial equilibrium and the transformation of calculation into simple geometric operations reduces the amount of necessary expertise and opens up structural design to empirical and intuitive understanding, thereby allowing for increased referentiality" (Kotnik & DAcunto, 2013). The constructive and generative nature of the vector-based operations of graphic statics allows the designer to continuously deform and adjust to different constraints on the bases of the force flow, thereby achieving the desired intersection between the structure's rational logic and the artistic concept of architecture. It enables architects and designers to take a more operational and communicative approach to design.

6. Design of the embodied structure

To describe the relationship between stable form and its force flow within bone structures, Viollet-le-Duc uses

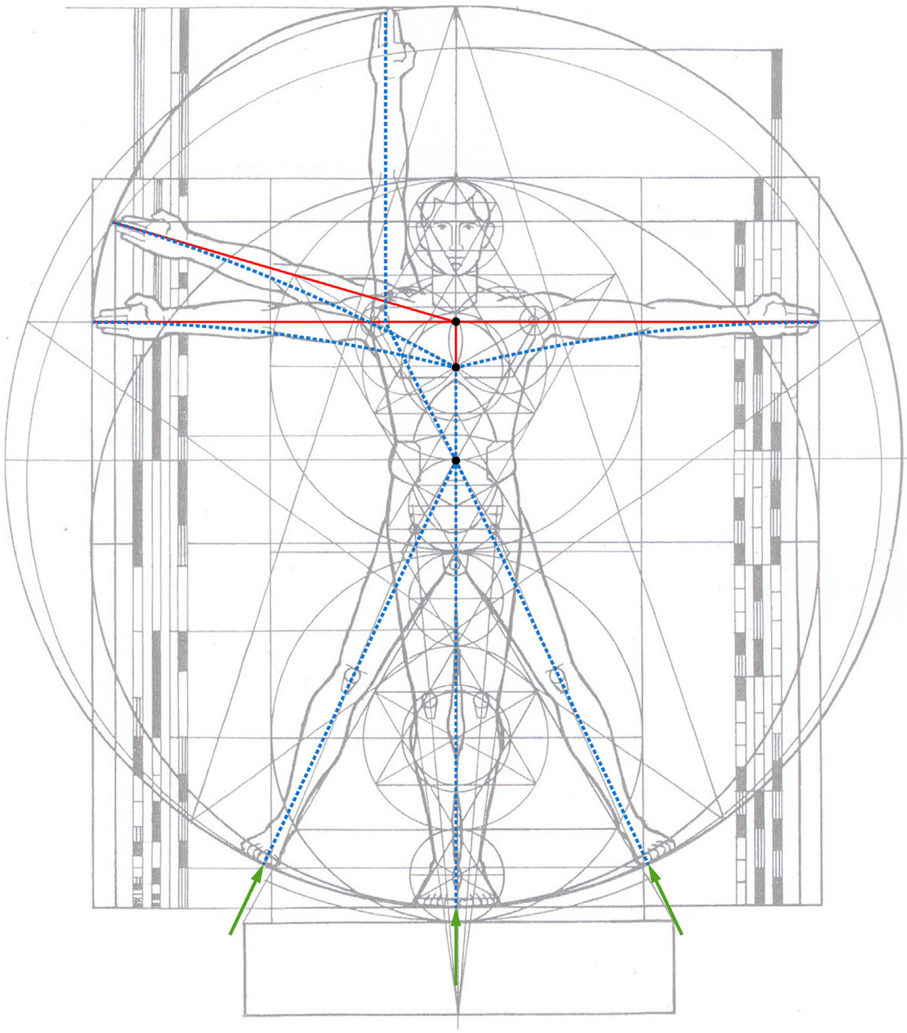

Fig. 6 Vitruvian Man cropped and erased measurements with the representation of graphic statics.

exploded diagrams, whereas Culmann uses graphic statics. However, they are all limited on the research of core-form of structure in terms of stability. In addition, this paper attempts to incorporate the art-form into the structural design process through embodied perceptual principles to design a pre-reflective structure that the human body can perceive and experience in the future.

To advance the neuropsychological embodied understanding of structures to a more operational level for design, deconstructing bodily gestures and movements in relation to structural design principles becomes critical. Neuroscientific research enables us to reduce the artistic dimension of structures' relatively abstract dimension to an expression of the degree of embodiment that can be created. That is, one gains an understanding of the mechanics of an architectural structure's "bodily" form by first grasping the mechanics of transmission in one's own body and the structure's relative relationship to our body. The critical part here is the ability to map and motivate the body structure to the architectural structure. Thus, depending on the architectural intent, we can employ a variety of degrees and types of structural embodiment to dialogue with the body.

6.1. Design of force flow and material distribution

The manipulation of graphic statics can directly influence the metaphor and guidance for the bodily schema. The distortion of the force flow based on basic geometrical operations allows for abundant structural and spatial variations. Additionally, taking embodiment as the basic concept, bodily schema can serve as the vocabulary, while graphic statics serves as the grammar. This function allows us to frame, bridge, cantilever, and materialize the structures according to the design concepts. Thus, we can construct a twofold embodied structure: *the design of force flow and the design of material distribution*. On the one hand, directing the potential representations of the structure on an abstract level is possible by directly operating and deforming the structural topological relations of the force flow. On the other hand, by designing approximate material allocations between form and forces to inform and guide the materialization of final structural forms to approach embodiment principles, constructing an art-from based on the structural core-from is possible.

For the design of the force flow, graphic statics facilitates a design-oriented understanding of the inner forces within a building structure that is an active engagement with the pattern of distribution of forces within space (Muttoni, 2011). By collapsing or splitting the forces (Fig. 7) or transforming the forces between tension and compression (Fig. 8a1—c1), graphic statics can bring the force flow approach or influence the compositions of the bodily equilibrium gestures and movements, thus resonating with the corresponding psychological balance and its emotions (Fig. 8a2—c2). Through the series transformation of the force diagram in Figures (a1) to (c1), the force flows of the graphic statics demonstrate their ability to correlate with the various bodily gestures in Figures (a2) to (c2), which can elicit different bodily feelings and emotions. Additionally, through the re-composition of the force flow units (a1), (b1), and (c1), we can construct a more complex global equilibrium. For instance, in the case of (d), they can be combined into Fig. 6 to create a global bodily equilibrium for the Vitruvian Man. This possibility opens up architectural form as a structural design topic by using the topological flexibility of force flow to guide the material allocation in space and tectonic expression.

Additionally, the freedom inherent in graphic statics design extends to the materialization of this pattern as structural elements. In general, graphic statics is an approach to structural design that is material-independent similar to Culmann's graphic statics analysis of bone morphology and historical discussion of bones and skin in architecture. In each case, the shape of the structural element is interpreted as the minimal envelope possible for the force pattern to be carried. By incorporating the yield stress or ultimate stress of a material as a parameter, such an interpretation of the force-form relation can result in the shaping of a structural element, which is a design decision. The material only needs to act as a medium for the transmission of forces through space. Consequently, no strict correlation exists between the inner force flow and the realized form.

Additionally, with the constructed force flow as an inscribed distribution pattern, the materialized envelope can be interpreted more freely and receive its shape in relation to other design criteria (Fig. 9). Thus, the constructed pattern of forces can be viewed as a diagram for the form of a structural element; it is not the form of the building structure but rather serves to inform it. Therefore, this correlation allows the force flow and the enveloping material to obtain a second layer of design freedom that can be integrated with the embodiment into the structural materialization process.

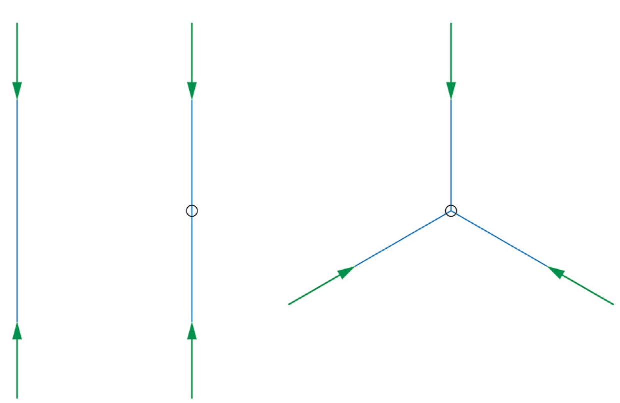

Fig. 7 By collapsing and splitting forces, the addition of an equilibrium point to a linear force flow creates a new force flow pattern.

6.2. Body as the method for structural design

By using bodily schema as a vocabulary and graphic statics as grammar, we can re-read the embodied expressions and interconnections present in various structures and develop them into a structural design method.

The perception of the body is implied or emphasized in many famous architectural structures. For example, the vertical force flow in the caryatids (Fig. 10) of the Temple of Erechtheion (406 BC) was sculpted as multiple female bodies rather than bare columns. Considering that its gesture could evoke people's bodily experience of supporting a heavy load overhead with an upright body (Similar to Fig. 8 b2), it structurally corresponds to a column's balanced load-bearing behavior in compression. As a result of the analogy between supporting bodily experience and structural geometry, the embodied perception of the structure's heaviness is stimulated, expressing a sense of stability, harmony, and the social metaphor of responsibility.

The structure of the entrance staircase in Studio di Architettura Livio Vacchini (1985) (Fig. 11) suggests a gesture resembling legs apart (similar to Fig. 8 a2). The massive solid structure employs the leg gesture as its vocabulary, assisting the structure in resisting the horizontal lateral thrust of the structure as a whole while also psychologically implying stability. Therefore, it alleviates the sense of instability generated by the thin walls on the ground floor's two sides.

Marcel Breuer's cantilevered roof structure at the entrance to the Whitney Museum (1966) (Fig. 12) can be interpreted as a vocabulary of straightened arms (similar to Fig. 8 c2), expressing the tension created by maintaining the arms horizontal for an extended period. The arms then become fatigued, creating a sense of tension and emphasizing the entrance's position through its unusual expression. Additionally, the complex geometry of the entrance stimulates a variety of embodied perceptions from various vantage points. For example, the bottom support resembles a tiny leg supporting a massive body, reinforcing the structure's expression.

In Villa Além (2014) by Valerio Olgiati (Fig. 13), the wall that encloses the courtyard of the building induces a seemingly unbalanced fold through the deformation of the force flow. This folding can easily provoke the past experience of bending or leaning forward of the body (Fig. 14), which through its unstable form provokes a sense of imbalance. The obliqueness-oriented instability and oppression expressed in this structure responded to the site's procession-like quality that Olgiati has consistently been instilled in the project (Woodman, 2015), and the leaning bodily vocabulary becomes the medium to express it.

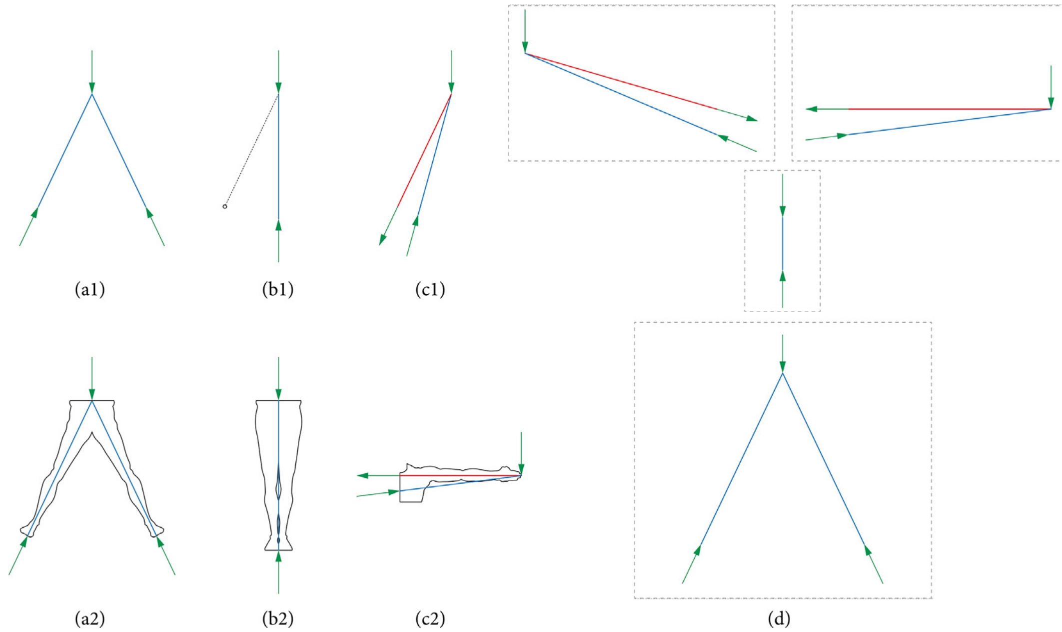

Fig. 8 Through the series transformation of the force diagram in Figures (a1) to (c1), the force flows of the graphic statics demonstrate their ability to correlate with the various bodily gestures in Figures (a2) to (c2). Additionally, through the recomposition of the force flow units (a1), (b1), and (c1), we can construct a more complex global equilibrium.

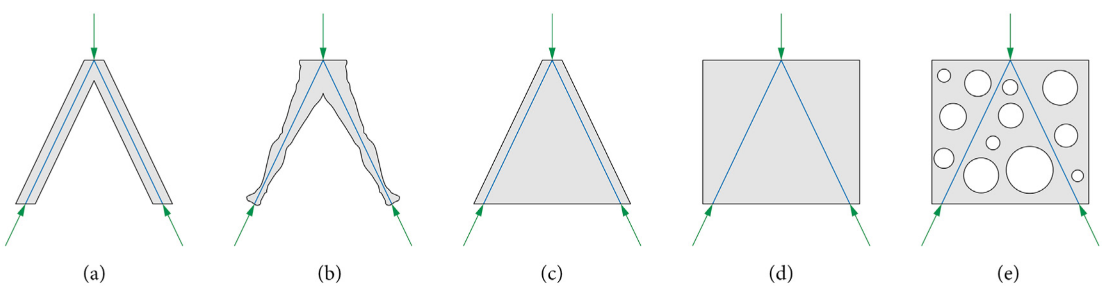

Fig. 9 Different materialized geometry based on the same force flow represents very different design concepts and the degree of embodiment they can offer.

Similarly, the way graphic statics constructs the relationship between structure and body not only can stimulate embodiment as in the previous cases but can also obscure

Fig. 10 Temple of Erechtheion, Athens. Photo: Sharon Mollerus. Source: flickr Creative Commons.

the structure's stimulation of embodied perception in accordance with the design intent.

In the Forsterstrasse apartment (Fig. 15) designed by Christian Kerez and Joseph Schwartz, the building achieved a discontinuity between the upper and lower floors of the structure via force flow distortion, thus breaking up the repetition and regularity in space and form (Kerez, 2009). The interruption in the flow of forces aroused by the misalignment of the wall, both on the façade and inside, implies the metaphor of an incomplete or dismembered body—in contrast to the balanced bodily experience between the limbs—evoking a sense of abnormality and curiosity and stimulating a rewarding mechanism of exploration and movement (Mallgrave, 2013). This skepticism stems from the perception-absence of holistic equilibrium relations: individuals are unaware that the slab is also suspended from a wall above (Fig. 16). Furthermore, the Forsterstrasse apartment is also characterized by the materialized form of the walls. Rather than directly responding to the flow of forces similar to a truss (Fig. 16), the structure is enclosed by similar-looking walls (similar to

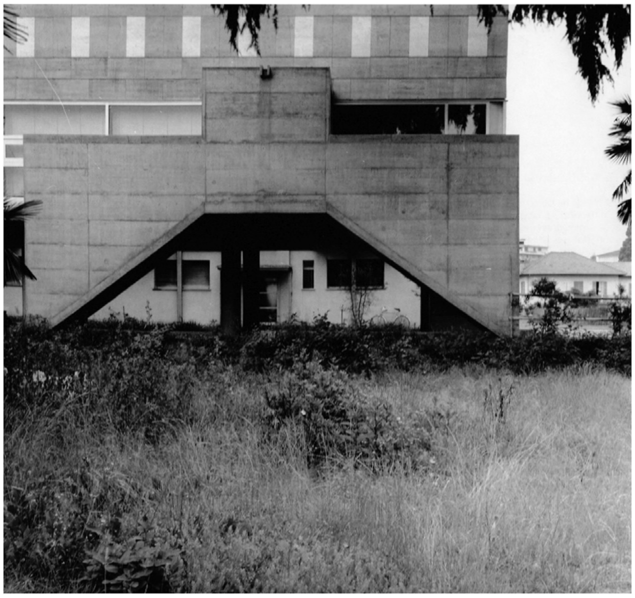

Fig. 11 Entrance of Studio di architettura Livio Vacchini. Source: Public domain.

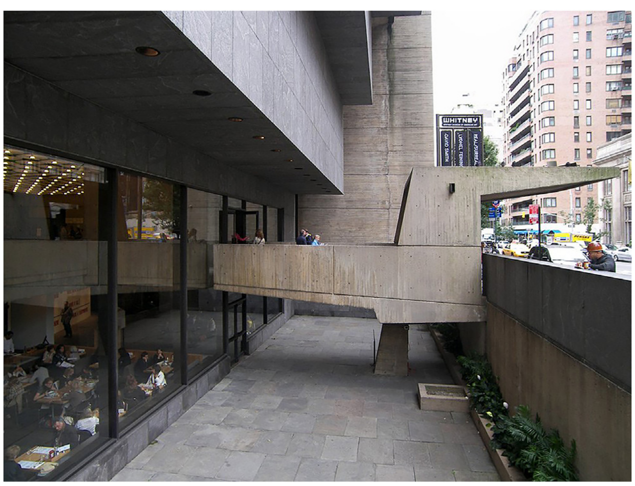

Fig. 12 Entrance of Whitney Museum. Source: Petr Kratochvíl/Fulbright-Masaryk Grant, online at: https://www.archiweb.cz/en/b/whitney-museum-of-american-art

Fig. 9 d). This materialization reduces the embodiment of individual structural elements but reinforces the relationship between walls, allowing for various possible interactions with the structures as one moves through them.

Similar to Forsterstrasse, Junya Ishigami's Kanagawa Institute of Technology (KAIT) Workshop (2008) (Fig. 17) blurs the embodied understanding of structure by splitting the force flow (Fig. 18). Not only do the ultra-thin columns themselves reduce the sense of embodiment, but Ishigami has materialized all the vertical elements, whether in compression or tension, as an identical white rectangular-shaped component. The presence of the columns in the building is thus extremely diminished (in contrast to the caryatids in the Temple of Erechtheion), emphasizing their relationship. The random-like structural expression and

Fig. 13 Villa Além. The view from the Garden. Source: Archive Olgiati (Villa Alem / Valerio Olgiati).

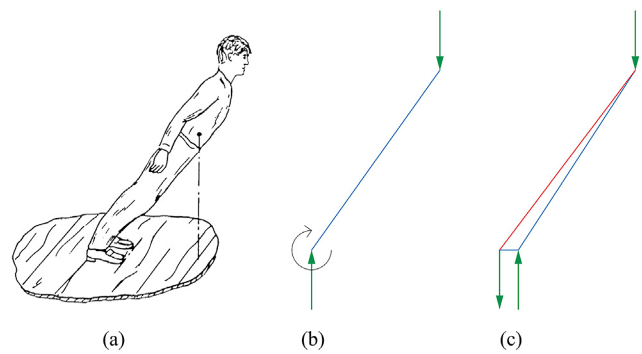

Fig. 14 (a) The tilted human body; (b) The expressed equilibrium regarding its geometry; (c) The actual equilibrium of the structure.

differentiated column spacing can imply various body movements. People can elicit different bodily emotions and meanings by making subconscious embodied judgments about the local arrangement of the columns based on tree arrangement, evoking the memory of people walking freely

Fig. 15 Façade of Forsterstrasse apartment. Source: Hisao Suzuki, online from https://www.subtilitas.site/post/156949653449/christian-kerez-apartment-building-on.

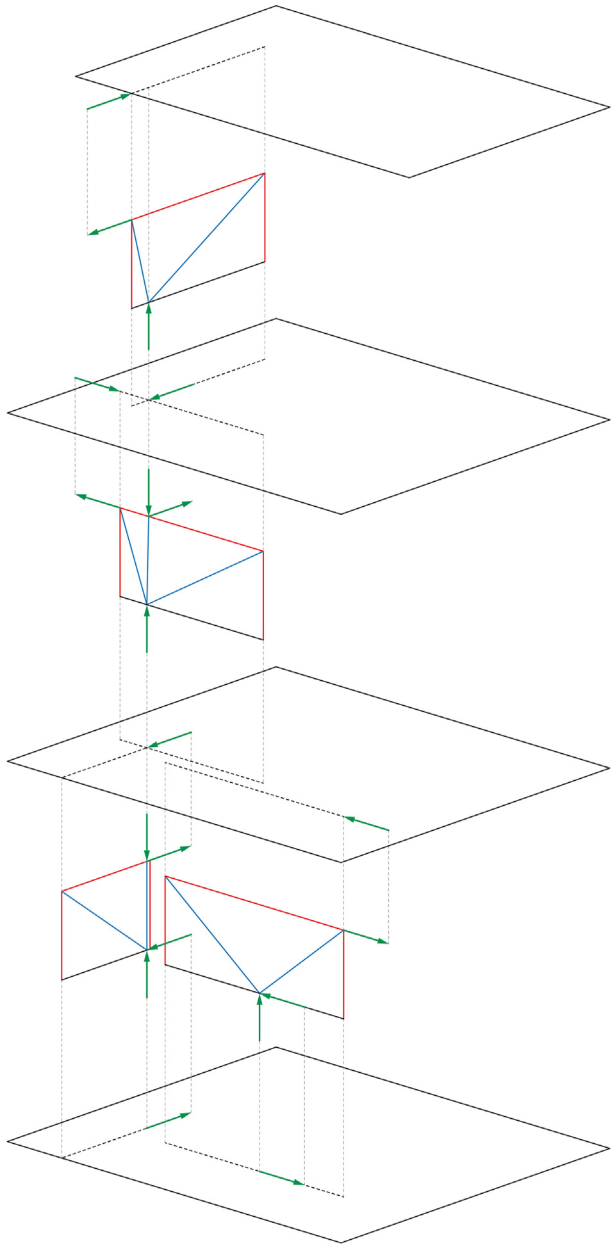

Fig. 16 Graphic statics depicts the simplified equilibrium condition and corresponding force flow in the Forterstrasse apartment. The walls are both supported and suspended from the slabs and walls below. By redirecting the forces within the slabs, the walls can move freely in the horizontal plane while maintaining equilibrium.

and comfortably through a tree-filled forest in the sunlight as Junya Ishigami imagined (Ishigami, 2008).

Among these cases, although the architects may be unaware, we can conclude that they are all attempting to actively introduce bodily schema and its corresponding emotions into structural design by distorting the common structural force flow or designing the material distribution, reinforcing or blurring the stimulation of the embodiment of the structure according to the architectural intention.

Fig. 17 Kanagawa Institute of Technology (KAIT) Workshop, Japan, Junya Ishigami. Source: Junya Ishigami + associates.

If the design of force flow reflects the impact of embodied perception on the structural relational system, the design of material distribution is more concerned with the physical representation of the structure. Using graphic statics as a guide, we can strike a balance between the physical and psychological aspects of the structure: between core-form, which requires static efficiency and minimal material distribution, and the art-form, which emphasizes perceptual aspects of space. However, the design of force flow and its materialization are not mutually exclusive; they always appear concurrently or in a circular fashion during the structural design process to address distinct spatial and architectural requirements.

With the advancement of digital technologies, the design of graphic statics has been expanded further: by defining a basic force-flow topological model, an infinite number of possible variations can be generated to interact with the design concept[10]. While the interaction of humans with their physical environment is abstract, force flow can be used to direct body movements while maintaining structural stability. Graphic statics can further integrate human perception principles into structural design processes by simulating human perception and behavior patterns using technologies such as virtual reality or agent-based simulation.[11] Consequently, the relationship between human perception and structural design is continuously optimized.

[10] See for example the recent research 3D Graphic Statics and its application on Machine learning: Saldana Ochoa K, Ohlbrock PO, D'Acunto P, Moosavi V. Beyond typologies, beyond optimization: Exploring novel structural forms at the interface of human and machine intelligence. *International Journal of Architectural Computing*. July 2020.

[11] See for example the review of scientific methods for measuring and experiencing architectural spaces: Şule Taşlı Pektaş. A scientometric analysis and review of spatial cognition studies within the framework of neuroscience and architecture, *Architectural Science Review*, 2021, 64:4, 374—382.

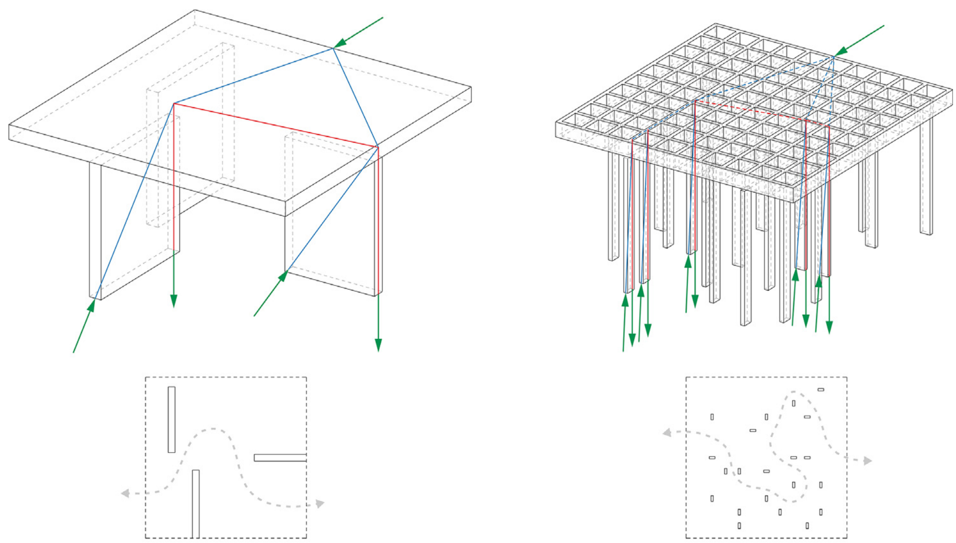
(a) (b)

Fig. 18 In KAIT, the simplified equilibrium condition is represented via graphic statics. (a): walls take up the equilibrium condition under horizontal force, and the composition of walls defines the human circulation; (b): when the walls in (a) are subdivided into a series of dense columns, the equilibrium condition in KAIT is approached. When a horizontal force is applied, the columns' pre-stressing and density may resolve the issue similarly to how walls do. In this case, the arrangement of the columns could subtly and softly imply the availability of human circulation and possible functions.

7. Conclusion: the embodied structure

Architecture, as a discipline, needs to be more open to the more comprehensive challenges posed by contemporary society in all of its aspects. The architect and structural engineer must also act as a composer that orchestrates building structures into the synchronization of technology, function, emotion, and aesthetics through the senses.

If Viollet-le-Duc's anatomical perspective on building structures inspired by biology allowed for a significant shift in the physical equilibrium of designing architectural structures, neuroscience discoveries would allow for a "paradigmatic shift" (Eberhard, 2009) or "sensorial revolution" (Jelić, 2015) in the perceptual equilibrium through the artistic dimension of structures. Taking body and embodied principles as the method, the application of Cognitive Neuroscience findings to architecture and structural design via graphic statics could result in a new and clearer scientific perspective on structural operation, thus achieving an embodied structural design thinking that connects structure, space, and the body. This idea is very similar to Julius Wolff's description in 1870 of Culmann's ability to see Meyer's specimens as "an extraordinary piece of luck for science" (Wolff, 1978, p. 111). A series of neuroscientific discoveries, most notably the study of proprioception, have enabled us to reconceptualize and rethink the relationship between bones and skin or the ontological and representational dimensions of structural design practice. Unlike the majority of current structural design methods, which focus exclusively on force and form, the embodied understanding of structural design encompasses both the initial and subsequent phases of structural design, transcendences structural art from an engineering perspective based on the dry "technical truth" of *Efficiency*, *Economy*, and *Elegance* (P. Billington, 1983), into an "artistic truth" that can be incorporated further into human perceptions and behaviors by determining the degree to which the structure's design and its materialization are relevant to embodiment.

In practice, embodied structural thinking enables the architect and structural engineer to communicate more efficiently and seamlessly by intuitively understanding one another's intentions. In terms of education, embodied structure research may also contribute to future improvements in structural design education. Incorporating body-related diagrams enables students to grasp complex structural principles more quickly and clearly by evoking motor sensory memory through bodily experiences. In terms of health, investigating embodied structures enables us to understand better how psychological needs are expressed structurally. This process may benefit children and individuals with disabilities by assisting them in maintaining their physical and mental health. In the digital realm, investigating the embodiment of structures can aid in the development of the increasingly popular virtual reality interface and the comprehension of spatial perception, specifically the simulation of gravity and equilibrium associated with structures. Additionally, the embodied structure can potentially reintroduce a new definition of "sustainability" into structural design: the capacity to provide a range of distinct and varied experiences rather than fixed functions or spaces. Finally, it may provide a new perspective on the reuse of space.[12]

Embodied structural thinking can enable a building structure to surpass its load-bearing capabilities and transform the structural design from a collection of incomprehensible numbers into a medium that connects the materiality of architectural representations with the abstraction of culture and aesthetics, thereby bringing structures to life.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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[12] To study examples of the potential application of embodied structural design for education, see Whitehead, Rob, "Supporting Students Structurally: Engaging Architectural Students in Structurally Oriented Haptic Learning Exercises" (2013). *Architecture Conference Proceedings and Presentations*. 41; for wellbeing, see Upali Nanda, Debajyoti Pati, Hessam Ghamari & Robyn Bajema (2013) Lessons from neuroscience: form follows function, emotions follow form, *Intelligent Buildings International*, 5:sup1, 61—78; for virtual reality, see Pasqualini I, Blefari ML, Tadi T, Serino A and Blanke O (2018) The Architectonic Experience of Body and Space in Augmented Interiors. *Front. Psychol*. 9:375.

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