PHILOSOPHICAL TRANSACTIONS B

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Cite this article: Fragaszy DM, Kelty-Stephen DG, Mangalam M. 2024 How bipedalism shapes humans' actions with hand tools. *Phil. Trans. R. Soc. B* **379**: 20230152.
https://doi.org/10.1098/rstb.2023.0152

Received: 2 October 2023
Accepted: 9 May 2024

One contribution of 14 to a theme issue 'Minds in movement: embodied cognition in the age of artificial intelligence'.

Subject Areas:
behaviour, cognition, evolution, biomechanics

Keywords:
body+object system, cascade dynamics, development, embodiment, evolution, postural control

Author for correspondence:
Dorothy M. Fragaszy
e-mail: doree@uga.edu

How bipedalism shapes humans' actions with hand tools

Dorothy M. Fragaszy[1], Damian G. Kelty-Stephen[2] and Madhur Mangalam[3]

[1]Department of Psychology, University of Georgia, Athens, GA 30602, USA
[2]Department of Psychology, State University of New York at New Paltz, New Paltz, NY 12561, USA
[3]Division of Biomechanics and Research Development, Department of Biomechanics, Center for Research in Human Movement Variability, University of Nebraska, Omaha, NE 68182, USA

DMF, 0000-0002-4010-4993; DGK-S, 0000-0001-7332-8486; MM, 0000-0001-6369-0414

The task for an embodied cognitive understanding of humans' actions with tools is to elucidate how the human body, as a whole, supports the perception of affordances and dexterous action with objects in relation to other objects. Here, we focus on the relationship between humans' actions with handheld tools and bipedal posture. Posture plays a pivotal role in shaping animals' perception and action dynamics. While humans stand and locomote bipedally, other primates predominantly employ quadrupedal postures and locomotion, relying on both hands and feet to support the body. Drawing upon evidence from evolutionary biology, developmental psychology and performance studies, we elucidate the influence of bipedalism on our actions with objects and on our proficiency in using tools. We use the metaphor of cascades to capture the dynamic, nonlinear transformations in morphology and behaviour associated with posture and the use of tools across evolutionary and developmental timescales. Recent work illustrates the promise of multifractal cascade analysis to reveal nonlinear, cross-scale interactions across the entire body in real-time, supporting the perception of affordances for actions with tools. Cascade analysis enriches our comprehension of real-time performance and facilitates exploration of the relationships among whole-body coordination, individual development, and evolutionary processes.

This article is part of the theme issue 'Minds in movement: embodied cognition in the age of artificial intelligence'.

> There is no such thing as a naked brain.
> — Louise Barrett [1, p. 191]

1. Tooling as radical embodied cognition

This report explores the origins and nature of humans' use of hand tools, a form of embodied cognition. We start by considering the term 'embodiment'. At its simplest, 'embodiment' states an obvious fact. Animals and plants behave; their bodies engage their environment through movement. The body enables and accomplishes behaviour; the behaviour of animals and plants is necessarily embodied. However, the term has come to mean something more in psychology and neuroscience, presenting a family of views about cognition as the process of the body engaging with the environment. One entity in this family is particularly interesting in this article: radical embodied cognition. 'Radical embodied cognition' in its current formulation in psychology derives from the work of American naturalist philosophers John Dewey and William James, among others, from the second half of the nineteenth century to the early twentieth century [2–4], developed by Eleanor and James Gibson in

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the mid-twentieth century as ecological psychology [5–8], and elaborated in the decades since by Blau & Wagman, Bruineberg *et al.*, Chemero, Heft, and Stoffregen *et al.* [9–13], among others. Barrett [1] provides a comparative treatment of radical embodied cognition manifested in various species of non-human animals, from spiders to primates. As Chemero [11] and Barrett [1] note, radical embodied cognition does not need and does not use computational metaphors for cognitive processes, and we agree with that view [14]. In this article, we work to provide an embodied understanding of humans' actions with hand tools using evolutionary, developmental and performance evidence.

We extend our previous work [15] on a theory of 'tooling'—a term we coined to emphasize the actions rather than the objects used when animals use a grasped object as a tool (i.e. hand tools in humans)—that focuses on the dynamics and spatiotemporal relationships of actions with grasped objects to achieve mechanical goals (e.g. altering another object or surface). We presented the theory to support prospective hypothesis testing and principled comparisons across species about this form of action. Conventional definitions of 'tool use' in the literature referring to non-human animals had been proposed to identify and classify qualifying cases [16,17], but not to examine the mechanisms by which the relevant actions occur nor the form of the performance. Because our theory focuses on the performance of actions with objects, we use the verb 'to tool' and its gerund form 'tooling' (denoting the activity) rather than 'to use tools' or 'tool use'. We hope that using this new term will help the reader keep the embodied character of these skilled movements and our focus on their performance at the forefront of their attention.

Tooling provides an apt domain of activity in which the radical embodiment perspective can guide inquiry. As Martin Heidegger noted, a tool is 'ready-to-hand' to the person using it; the person perceives the tool as ready to use to reach some goal [18]. Tooling involves recruiting an external object into the body system, creating a body+object system, which, in turn, is nested within the [body+object]+environment system [15,19]. For example, in a typical sequence in which a hammer is used to nail two boards together, the person grasps the hammer by the handle, positions a nail against a board laid on top of another, and nails the boards together. When using the hammer in a functional, familiar way like this, the person experiences the hammer as part of a unified system with the body; the hammer is 'ready-to-hand', and attention is directed to acting with the hammer to strike the nail into the two boards, rather than to the hand or to the hammer itself. Heidegger's phrase 'ready-to-hand' captures the phenomenological aspect of the person-plus-object system acting on their environment [18]. Cognitive scientists often describe this feeling as having a sense of agency with the hammer. Here, the sense of agency is broadly defined as the feeling of controlling one's actions and, in the context of tooling, of controlling the handheld object and its impact on the environment when used as intended [20,21]. A sense of agency while tooling is accompanied by a shift in perceptuomotor attention from the body to the specific tool component that makes contact with the target object or surface and to the surface it contacts. This attentional shift has been referred to as the 'distalization of the end effector' [22]. In the more general context of touching a surface with a grasped object, perception of the relationship between the surface and the object (such as feeling a surface yield when poked with a stick) has been described as an aspect of dynamic touching [5,23] and as distal touch [24,25].

Tooling entails several perceptuomotor processes, including (i) perceiving spatial relationships among objects and surfaces; (ii) developing agency over objects connected to the body, making them 'ready-to-hand'; and (iii) controlling bodily movements to meet functional requirements of tooling [15,26]. These processes are not unique to tooling; they can be observed in various non-tooling contexts and degrees across different species, as reviewed by Mangalam & Fragaszy [19]. Thus, it is unsurprising that tooling is observed in many animal species [17]. However, humans exhibit notable differences in tooling compared with all other species, even all other primates. While other primate species possess similar grasping appendages and sensory systems as humans (such as binocular vision and five-fingered hands with dense sensory receptors in the fingertips), their tooling is significantly more straightforward than humans' [19]. For example, to our knowledge, no animal has been observed moving two objects simultaneously in a reciprocal, coordinated manner, as humans do when using a knife and fork to cut a piece of food into smaller portions. Humans use diverse natural and manufactured tools for myriad purposes, in myriad ways, and myriad settings; this is not true for any other species.

The human advantage over other species in tooling rests on differences in all three perceptuomotor processes—spatial perception, sense of agency and controlling movement. The shift to bipedal posture and locomotion over millions of years in the hominin lineage, and developmentally over the first few years of life, significantly altered how our bodies maintain postural equilibrium compared with other primates. These alterations had (and have, developmentally) significant cascading effects on perception and action beyond maintaining a stable equilibrium in space. As noted by Gibson [5], dynamic orientation is fundamental—for terrestrial animals like humans, the body's orientation and movement in relation to gravity and the ground surface are crucial for postural equilibrium and directed movement. The control of the body's movement to maintain postural equilibrium engages numerous interconnected elements of the body, including the musculoskeletal system, vestibular system and often the visual system [27–29]. In tooling, as in other activities, introducing an object into the system introduces additional elements and nonlinear cross-scale interactions, making analysing these movements challenging. The later sections of this article present an approach to analysing bodily movement cascades during manual object manipulation.

Before we analyse movements in real-time, we synthesize evidence across other timescales—evolutionary and developmental—about how bipedalism underlies human perception and action in tooling. The article is organized as follows: in §2, we briefly consider how primates use the hands in locomotion and feeding, the evolution of bipedalism in hominins, and the concurrent appearance of stone tools and increasing dependence on bipedalism on hominins using tools. Next, §3 addresses humans' spatial perception and agency with objects, which is evident in tooling (and other contexts). In §4, we show how the development of upright stance and locomotion has profound organizing effects on children's spatial perception and probably on their developing sense of agency with grasped objects. Then §5 introduces the concept of suprapostural dexterity to describe how humans adjust posture and movement while incorporating an object into the body system. Finally, §6 introduces multiplicative cascades as an appropriate metaphor for embodied cognition and explains how cascade dynamics can be modelled computationally. We present findings from studies using cascade dynamics that illustrate the deep connection in humans between postural regulation and perception of affordances and actions while handling objects. We aim to show this new approach's promise for understanding tooling as an embodied phenomenon.

2. Human manual dexterity through the lens of primate evolution

(a) Locomotion and positional behaviour in quadrupedal primates

Primates first appear in the palaeontological record about 55 Myr ago. Primates, as mammals, are quadrupeds, relying on their four jointed limbs to support the body's long axis in a horizontal position in relation to gravity. Early primates inhabited broadleaf forests. With forward-facing eyes and pentadactyl unwebbed hands and feet, they grasped branches securely with all four limbs. They fed by visually locating a food item, grasping it in one hand (leaving three limbs to support the body), and bringing it to the mouth. Although their morphology and ecology underwent significant changes as primates diversified (into two suborders, five superfamilies, 17 families and hundreds of species extant for the time being), specific primitive characteristics remain shared features among all primates, such as slow life history, good visual acuity, binocular vision for enhanced depth perception, pentadactyl grasping extremities, diagonal-sequence footfall patterns, hindlimb dominance in locomotion and visually guided manual prehension [30]. All primates employ visually guided movements of their forelimbs to reach for and grasp food with one hand, closing their digits towards the palm, as described in Fragaszy *et al*. [31]. Thus, since the early stages of primate evolution, the arms and hands of primates have served dual purposes: supporting body weight and grasping food to bring it to the mouth. As Presuchoft noted, 'Body shape adapted for an arboreal lifestyle also smooths the way towards bipedality. Hindlimb dominance, length of the limbs in relation to the axial skeleton, grasping hands and feet, mass distribution (especially of the limb segments), thoracic shape, rib curvatures, and the position of the center of gravity are the adaptations to arboreality that also pre-adapt for bipedality' [32, p. 363]. Considering the feet, Patel *et al*. [33] show that the muscles of the feet are activated differently than those of the hands during quadrupedal locomotion. The functional differentiation between forelimbs and hindlimbs in quadrupedal primates is one of the several biomechanical characteristics that set the conditions for the subsequent evolution of refined manipulation capabilities and bipedality in hominins. Hominins' feet evolved from grasping appendages with opposable halluxes (as in all other primates) to 'stiff, propulsive levers' [30, p. 34] with the hallux parallel to the other toes–feet that support the body in dynamic balance on flat surfaces. Hominins' hands evolved differently by elaborating grasping functions in diverse ways [34].

Interestingly, rats also use a single extremity to grasp and transport food to their mouths [35]. Shared characteristics in limb transport and hand or paw shaping during skilled reaching have led Sacrey *et al*. [35] to propose that skilled reaching is homologous between rodents and primates, which aligns with the presumed close phylogenetic relationship between these two groups [36]. Furthermore, Sacrey *et al*. [35] suggest that skilled reaching is probably an exaptation[1] in both clades that originated from stepping movements associated with locomotion. If so, the sophisticated forelimb movements involved in skilled reaching and prehension in primates evolved from, and remain constrained by, ancient locomotion patterns and corresponding anatomical structures. The shared locomotor origins of skilled reaching in rodents and primates bring a new appreciation of the probable links between locomotor adaptations and manual activity. Like all other mobile animals, humans rely upon effective locomotion and postural support. It is wise, therefore, to consider humans' manual activity in light of the postural background conditions that support locomotion and our unusual bipedal locomotion pattern and bipedal stance, together labelled bipedalism.

(b) Evolution of bipedal posture and locomotion

Human manual dexterity co-evolved with the human specialization in bipedal stance and locomotion. Thus, it is helpful to appreciate the mosaic, messy pattern of evolutionary changes in locomotor patterns in human ancestors. We start with gait patterns in primates. Many arboreal mammals adopt diagonal-sequence diagonal-couplet (DSDC) quadrupedal gaits (left hind, right fore, right hind and left fore; figure 1*a*), presumably affording secure support in arboreal environments [39,40]. DSDC gaits minimize periods of unilateral support by ipsilateral limbs and allow the opposite hind foot to take hold of the support if the leading forefoot fails to achieve a secure grip [40]. The DSDC pattern appears in non-human primates walking quadrupedally, humans crawling on all fours and even in humans walking bipedally [41], as humans typically swing their arms while walking unless actively adopting some other action with the arms (e.g. holding an object with two hands). The organizing effects for humans of using this gait pattern are helpful in rehabilitation following injury or illness (when practising quadrupedal locomotion facilitating contralateral limb coordination is considered helpful for regaining mobility [42] and in therapeutic practice with children with sensorimotor underdevelopment [43]).

Primates supplement the DSDC pattern with various other locomotor modes [38] and generally display more variable limb coordination than other mammalian groups. For example, hylobatids, atelines and hominids exhibit suspensory locomotion (suspending the body under tree branches; figure 1*b* [30,34,38]). Anatomical features supporting suspensory locomotion appear in fossils of hominins and are retained in contemporary humans [44,45]. The shoulder and upper-limb mobility associated with suspensory locomotion allows humans to use overhand motions to throw objects forcefully. Thus, anatomical characteristics that evolved to support locomotion have subsequently come to support entirely different functions [46]. Furthermore, the emancipation of limb movements is evident in the variable locomotor patterns exhibited by primates, which allow limbs to be used in various ways to handle objects. In short, dexterity related to handling objects and tooling reflects in part exaptations of

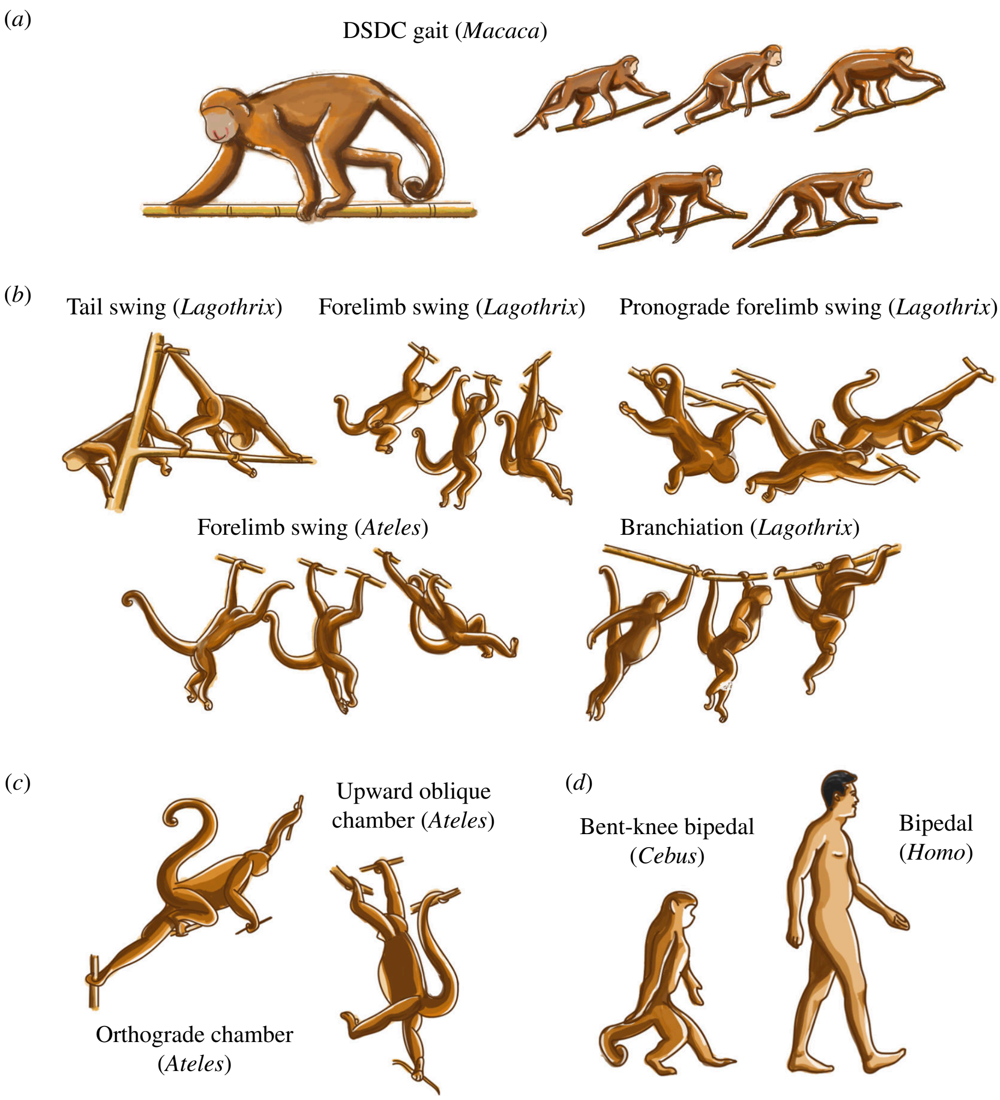

Figure 1. Primate locomotor and postural modes. (*a*) DSDC quadrupedal gait in the genus *Macaca*. (*b*) Suspensory locomotion in the genera *Lagothrix* and *Ateles*. (*c*) Non-suspensory clambering gait in the genus *Ateles*. (*d*) Bent-hip bent-knee bipedal locomotion in the genus *Cebus* and bipedal locomotion in the genus *Homo*. Adapted from Hunt *et al*. [38].

physical characteristics first selected for arboreal locomotor functions, including soft tissues that do not fossilize (e.g. neural and muscular systems).

Bipedal posture and locomotion are thought to have emerged in primates climbing and moving in trees [44,47,48]. Extant non-human primates use bipedal postures in trees more often than on the ground and use assisted bipedal postures more than unassisted bipedal postures [49]. Reaching in an upright stance, assisted by using one hand or (in some monkeys, but no apes) the tail to grasp support (figure 1*c*) allows animals to move about on small supports more securely and thus for even larger-bodied animals to harvest foods from small terminal branches and in general to reach a greater area [38]. Early hominins probably employed diverse bipedal behaviours, including walking on the ground, but they retained anatomical characteristics (e.g. long forelimbs and curved phalanges) suggesting they continued to climb and move about in trees [45,50,51].

While the emphases of different scholars on particular factors vary, the current consensus is that the evolution of obligatory bipedalism in *Homo* reflects selection for locomotor efficiencies and behavioural capacities to meet a combination of changing ecological and physiological requirements. For example, dietary changes, increased carnivory, larger body size, expanded brain volume and a climatically driven shift in habitat towards more open vegetation (requiring more extended travel between feeding sites) may all have played roles in the selection in *Homo* for a greater preponderance of bipedal stance and an elaborated bipedal repertoire (e.g. sustained running) [52,53]. Today, we stand as obligate bipeds, with a mosaic of anatomical and movement elements retained and modified from our more arboreal ancestors (figure 1*d*). The emergence of affordances within the animal/environment system, facilitated by the efficient bipedal postural organization of hominins and the accompanying musculoskeletal, neuronal and perceptuomotor changes from their quadrupedal ancestors, paved the way for a significantly distinct way of life for our predecessors.

(c) Bipedality and the appearance of manufactured tools

The earliest archaeological evidence of manufactured objects for percussion (worked cores, percussors and flakes, among other items) dates to about 3.3 Myr ago, nearly a million years before the earliest fossils attributed to *Homo* [54]. These objects have been attributed to Australopithecines, which probably used a human-like striding bipedal gait but probably had less endurance when moving bipedally than do modern humans, and which probably continued to climb trees and move in them as a regular part of daily activity [55]. Bipedal stance is not necessary for the essential actions in percussive tooling, such as holding a stone and striking it on another object, as when apes, monkeys and humans use stone hammers (figure 2) [56–58].

Although bipedal stance is unnecessary for percussive tooling, obligate bipedalism co-evolved in humans with tooling and manufacturing tools. More stable bipedal postures, more efficient strides and greater endurance may have allowed early *Homo* to use tools more effectively and thus increase the frequency and diversity of such actions compared with ancestral hominids. The discovery and widespread use of the earliest known stone-knapping technology (Oldowan technology, named for the place where the first tools of this type were discovered, Oldovai Gorge in Tanzania) dates from 2.6 Myr ago [59] or a few thousand years earlier [52], during the lower Palaeolithic—then followed a long period of slow incremental change in the form of manufactured tools [59]. Considerable diversity in locomotor morphology and the morphology of the hand is present in fossils across *Homo* from 2 Myr ago until the appearance of *Homo sapiens* and *Homo neanderthalensis* in the Middle Stone Age [60,61]. The appearance of *Homo sapiens* about 300 000 years ago [62] also coincides with the arrival in the archaeological record of more refined blades and projectile points. Using a sharp blade or point forcefully is facilitated by an upright stance to recruit the whole body, whether holding a stone in hand or a spear. Using hafted projectiles (such as spears) is 'a niche-broadening technology' [63] that reduces the risks of preying on large, dangerous animals and increases rates of return when hunting smaller, fast-moving animals. In short, adopting thrown projectile hunting techniques is assumed to have broadened access to rich food resources.

The anatomical transformations associated with bipedalism evident in the fossil record, coupled with simultaneous alterations in the frequency of deposition and forms of stone tools found with hominin fossils, strongly suggests that bipedalism in hominins is part of a cluster of evolving traits that propelled tooling beyond its traditional role as an optional, opportunistic activity, as it remains today in apes and monkeys [64], to an obligate activity in humans. We propose that bipedalism laid the foundational postural groundwork for advancements in tooling in the hominin lineage. The concept of 'suprapostural dexterity' signifies the body's ability to maintain a resilient yet adaptable support base during focused behaviours extending beyond the body, such as pointing, reaching or carrying objects [26,65]. This concept provides a new way to think about the role of bipedalism in tooling. Considering tooling as a manifestation of suprapostural dexterity sets the stage for thoroughly examining the interactions taking place within the body+object+environment system, as envisioned in ecological psychology and facilitated by state-of-the-art nonlinear analytical techniques [66]. In a later section, we take up this challenge by showing how cascade analysis can be useful for exploring postural contributions to humans' actions with handheld objects.

3. Spatial perception and sense of agency

(a) Allocentric spatial perception and action with grasped objects

Humans precisely align features of grasped objects with features of other objects or fixed surfaces—skills used in tooling. These actions rely on using an allocentric frame of reference, meaning the actor references the spatial relationship of external objects to each other rather than to their own body. Vision most readily supports using an allocentric frame of reference in sighted individuals. Blind individuals use an allocentric frame of reference in some conditions through haptic cues [67]. In sighted individuals, an allocentric frame of reference is evident from early childhood [68,69].

By contrast, those non-human primates studied to date are much less proficient at aligning objects [70,71]. When presented with either a straight stick, a T-shaped stick or a tomahawk-shaped stick to fit into a matching cutout on a flat surface, capuchin monkeys (*Sapajus* spp.) and chimpanzees (*Pan troglodytes*) performed more poorly than 2-year-old children [68]. Neither species reliably aligned objects along even one axis when they first touched the surface with the stick, and they did not systematically vary their behaviour to aid the discovery of the affordances of combining the stick with the surface beyond sliding the stick along the surface (which could provide haptic information about the location of the cutout). They inserted the object only after persistently sliding it over the cutout until a corner of the stick eventually fell into the cutout. Then, they worked to push the rest of the stick into the cutout. The striking difference between these species of non-human primates, both of which show percussive and probing tooling in natural settings [72], and even very young children in the ability to use an allocentric frame of reference to orient one object with another suggests one source of the differences between humans and other primates in their tooling abilities. Humans can readily use an allocentric frame of reference while handling objects; non-human primates do not. Thus, humans perceive affordances for actions with objects that non-human primates do not. Further studies presenting instrumental tasks involving allocentric spatial referencing, such as fitting and insertion, with additional species of non-human primates are needed to confirm this conclusion.

We take a moment to define 'affordance', a central concept in ecological psychology. Since its genesis in the writings of Eleanor and James Gibson [5,8], this concept has generated much discussion and definitions of affordances abound [73–75]. Here, we adopt Stoffregen's [75] definition of affordance as an emergent property of the animal/environment system[2] that exists only at the level of that system. An affordance is an opportunity for action by an animal; it is central to prospective control (through behaviour) to achieve an intention. In the aforementioned example, inserting the stick into the cutout can be accomplished using various methods, including aligning the stick's axes with those of the cutout, allowing it to slot in effortlessly. Humans readily perceive this affordance; however, non-human primates tested thus far do not. No apparent anatomical or sensory constraints impede their ability to perform this action.

Figure 2. The core activities of percussive tool use, like grasping a stone and striking it against another surface, are not contingent on obligate bipedalism, as exemplified by monkeys and humans employing stone hammers. (*a*) A long-tailed macaque (*Macaca fascicularis*) prising shellfish from a rock using a stone hammer while sitting. Credit*:* Michael Gumert. (*b*) Professor Dietrich Stout knapping a stone tool while sitting at Emory University's Paleolithic Technology Laboratory and (at right) a sample knapped tool. Credit*:* Gregory Miller.

(b) Agency with grasped objects

Humans typically experience a sense of agency while acting with grasped objects, as we experience the body+object as a unified system [5,76–78]. As mentioned above, our sense of agency takes on a particular form when we act with the grasped object to contact a target object or surface. Our attention and locus of perception and action move to the contact between the grasped object and the target object so that we feel the other object through the grasped object. For instance, we feel the hardness and smoothness of the surface of a table by sliding a grasped wooden rod across the table's surface in an exploratory action. Although housed in our bodies, our senses support perception at the distant point of contact between the rod and the table.

Now consider an example of tooling: using a needle to pierce canvas, as when mending a sail. We perceive the needle's tip piercing the canvas and ignore the pressure of our fingers on the needle (unless the fingers slip on the needle and that movement draws our attention). Our control of the needle depends upon our perceiving its movement through the canvas, illustrating that skilled tooling depends upon our sense of agency over the object's movement in our grasp. That sense of distal agency is bound up with perceiving the consequences of the object's movement, which entails a shift in our attention from the body to the object and its point of contact with the target object or surface. Attention to the relationship between two external objects, a form of allocentric spatial perception, is an essential feature of a sense of agency in tooling.

4. Development of walking and its ramifications for visuospatial perception and agency with objects

As pointed out by Adolph & Hock [79, p. 154] 'Motor development is enabling—it engenders new opportunities for learning and doing that can instigate cascades of development in far-flung domains'. The onset of walking indeed qualifies as a motor skill that powerfully affects opportunities for exploration and learning in diverse psychological realms [80], including language acquisition, attentional strategies and more [81] in a process that Bornstein *et al*. [82] describe as a developmental cascade. Infant humans practise walking with enthusiasm and persistence [83], just as earlier in life, following the development of stable sitting, infants persistently practise reaching and grasping [84].

(a) Optic flow enables visual-postural coupling

How the development of crawling and walking impact psychological development has been studied creatively by many developmental psychologists (see [81,85–87] for reviews). One must be cautious about inferring relationships between bodily processes merely based on the temporal proximity of new achievements during the second year of life, as change occurs rapidly across virtually all body systems in this period. However, postural and locomotor processes intimately affect visual perceptual processes, suggesting the onset of walking could plausibly be linked to changes in visual-spatial perception. Studies with typically developing infants transitioning from no locomotor ability to crawling and from crawling to walking have shown that developing postural control in these initially new activities is linked with the visual perception of self-movement, described as ‘optic flow’ [88]. Anderson *et al*. [89] propose that the onset of hands-and-knees crawling ‘presses’ human infants to map visual information onto action patterns in new ways as postural control develops.

In adults, visual-postural coupling of the whole body incorporates information from optic flow, particularly lamellar (rotational) optic flow experienced when the eyes, head or body rotate, or the body moves on a curved path, as illustrated by studies with an experimentally arranged ‘moving room’ [90,91]. In a moving room, the side and front walls can be moved forwards and backwards on rollers, optically simulating self-movement for a stationary person inside the room even though the floor is stationary [92]. (Recently, virtual reality versions of this paradigm have been developed [93].) Infants begin responding to peripheral optic flow in a ‘moving room’ with whole-body postural shifts at about the time they begin to crawl [94]. Children’s postural response to optic flow in the moving room continues to develop for several years as they become differentially sensitive to flow in peripheral (as opposed to central) vision [88]. Experiences moving themselves underlie infants’ and children’s developing differentiation of perceptual information and greater attention and responsiveness to optical flow [81,86,94–96].

As children transition from crawling to walking, their visual experiences and behaviours undergo significant transformations [97,98]. Walking infants exhibit increased mobility, covering greater distances at higher speeds than their crawling counterparts. Their expanded field of vision includes the ground and surrounding vertical surfaces and objects. Additionally, they engage more actively with distant objects, moving to them and playing with them. Notably, their interactions with carers often involve bringing objects to them [99]. Heiman *et al.* [100] discovered that young children, whether walkers or crawlers, are keen to hold and carry small objects and to avoid dropping them while in motion. Walkers, perhaps surprisingly, have a lower likelihood of falling when carrying an object compared with walking hands-free [101]. Walkers tend to explore grasped objects visually and manually more frequently while standing than walking [100]. In their studies, Claxton *et al.* [102,103] observed that newly standing infants exhibit sways of lower magnitude but more complex patterns when holding a toy versus standing with empty hands. This suggests that humans possess task-dependent postural control from the onset of standing. Overall, these findings underscore humans’ motivation, evident from infancy, to grasp and explore objects, with bipedal posture supporting and constraining these activities, depending on context.

(b) Development of allocentric spatial frame of reference

Between 16 and 24 months of age, some months after they begin to walk (at around 1 year of age, in Western, Educated, Industrialized, Rich, Democratic (WEIRD) cultures [104,105]), children master two different tasks with a grasped object that benefit from the use of an allocentric frame of reference: inserting a disk held in one hand into a slot [106] and moving a rake laterally towards an item to pull it in [107]. Although children can put their hand through a slot (using an egocentric frame of reference, the body to the object) at 16 months of age, they cannot align the disk to the slot until several months later [106]. Children also become able at about 2 years of age to insert an object into a matching aperture by adjusting the object’s position after bringing it to the appropriate aperture (figure 3; [108]). A year later, children adjust the object’s orientation while moving it towards its target aperture. Eventually, they translate and rotate the object simultaneously [69,109], although accomplishing this task more slowly than adults, even at 5 years of age [110]. Children younger than 18 months can use a rake to pull in an item, but only if that item is placed in front of the blade of the rake and a straight pull of the rake is sufficient [107]. In short, when attempting to rake in an object where they should align the rake with the object, and when attempting to insert an object through an aperture, children can execute the required gross bodily movements before they can meet the spatial demands of these tasks.

In a task tapping allocentric spatial memory, at 2 years of age (but not between 18 and 23 months), children could locate one object previously seen and hidden in an open field by using distal environmental features to identify the goal [111], and children 43 months and older could locate three objects hidden in this way. Thus, children demonstrated the emerging ability to use allocentric spatial memory about a larger space at the same age when they could first apply allocentric spatial relationships to control objects in peripersonal space, such as positioning a rake to a spatially separate target or aligning objects to an aperture. These findings indicate that allocentric framing is sufficiently developed by 2 years of age to support tooling and other manipulation skills and continues to develop for several years. Moreover, allocentric framing plays a crucial role in social interaction by enabling individuals to recognize affordances available to others and to understand others’ spatial perspectives, facilitating predicting others’ behaviour [112,113]. Thus, children encounter many situations where perceiving

Figure 3. A young child trying to align an object to an aperture in a shape-sorting toy. Children typically master this skill at about 2 years of age. Photo courtesy of Ellen Fragaszy.

allocentric spatial relationships is beneficial, and their skills at using allocentric framing in social and physical domains develop through childhood.

(c) Development of sense of agency and distal touch

Human infants exhibit prospective control of behaviour with their mouths, eyes and limbs before they can reach to grasp objects (reviewed in [114]), as when three month old infants kick a leg to activate a mobile tethered to it [115], to cite a classic example. A sense of agency when moving a grasped object to accomplish a goal occurs when the object becomes integrated into our experience of the body—as Alsmith [24, p. 344] puts it, '... in episodes of touch, one's experience of the object perceived is unified with one's experience of one's body, such that the two form interdependent parts of the same experiential whole'. We think it is probable that young humans' developing propensity to attend to the relationship between a grasped object and the target object or surface (allocentric referencing) will support perceptual learning about that relationship during action, thus enriching a sense of agency and perception of affordances. As discussed above, spatial perception is strongly impacted by the shift to an upright stance and learning to walk in early childhood. It seems probable that changes in spatial perception associated with the onset of bipedal posture and locomotion lead to changes 'downstream' in the richness of dynamic touch, perceptual learning about touched surfaces, and the resulting sense of agency with grasped objects—a developmental cascade of perceptual changes initiated by a change in the position of the body in space. We hope that empirical paradigms will be created to examine these ideas.

Do other species develop a sense of agency comparable to humans, particularly concerning actions involving grasped objects? Unfortunately, there is a lack of evidence on these points. While experimental paradigms to measure the sense of agency in direct movements (not using an object) using non-verbal variables have been developed for studies with human participants [116], they have not been applied to non-human participants. Thus, we can only give some suggestions for future investigation. Suppose the scenario presented above for developing distal touch and a sense of agency with a grasped object is correct. In that case, humans, in part owing to bipedalism, experience more established allocentric spatial perception and a stronger, more quickly developed and more elaborated sense of agency with grasped objects compared with other species, particularly other primates. Prospective studies involving humans and other species, evaluating individuals engaging in goal-directed actions with grasped objects throughout postural/locomotor development, will be crucial to assess these possibilities. It will be particularly interesting to examine the sense of agency in cockatoos (*Cacatua goffini*) and other parrots that recently have demonstrated impressive mastery using the beak and foot to control sticks to move objects they cannot reach directly [117] and inserting objects into matching apertures [118], the latter skill one that chimpanzees (*Pan troglodytes*) and capuchin monkeys (*Sapajus* spp.) did not achieve in a similar task [70].

5. Embedding tooling in postural context

(a) Postural sway supports suprapostural dexterity

In an earlier era, postural stability was thought to depend on minimizing postural sway. The thinking went like this: reaching for a glass is enough to topple us, as it abruptly changes the position of our centre of mass (CoM)—we must brace ourselves for the turbulence of our balance incident on such changes. In this earlier view, a stable posture minimizes postural sway associated with changes in the position of our CoM [119]. However, the ecological approach has led to a different, dynamic view: postural control is adaptive when it regulates sway to support a body completing its tasks in the environment, especially in tasks involving visuomotor hand coordination with the environment. Postural control appears intimately invested in whatever the hands are doing, generating task-supportive sway rather than simply reducing body movements [120–123]. Although reduced postural sway in one direction can promote manual precision in the orthogonal direction [124–126] and visual fixation on nearby objects [127,128], reducing postural sway does not always lead to improvement in task performance. Often, reducing sway in one direction to enhance aiming precision in the orthogonal direction will coincide with the release of more postural sway in that orthogonal direction—in some sense, satisfying task constraints may only reshape constraint without increasing it [124]. Learning a suprapostural task can change the average position of the postural centre of pressure (CoP) without entailing a reduction of postural sway. For instance, in a sequential-learning task, participants can learn to manually track a visible target in a repeated sequence of 15 changes in target position. Sway may wax and wane as participants improve at manually tracking the 15-step sequence, with posture showing progressively more constraint on average from anterior (i.e. forward) sway but increased and then generally stable amounts of sway around those average differences [129]. Increasing sway in the direction where we direct our attention can be perceptually advantageous. For instance, greater sway may generate more information through optic flow even for participants standing still [123,130,131]. To maintain ongoing poise while standing and determine where to take the next step, the standing participant needs information about the layout of surrounding surfaces (e.g. contiguous surfaces, overlapping or occluding surfaces). Typically, this information is most clearly available through forward locomotion [123,132], but if the standing participant hopes to take the first step, they will need comparable visual information. The optic flow produced by sway during quiet standing thus affords the sighted upright-standing organism richer information about the mechanical support for beginning to locomote again.

In summary, powerfully adaptable postural control incorporates sway to adjust to shifts in the CoM and forces generated through movement. This adaptive control is particularly important for movements that incorporate external objects into the body system, where they impact the forces in the system and alter the position of the system's CoM in ways that routinely go beyond what the body alone would experience through movement. In other words, such actions depend upon an elaboration of suprapostural dexterity, that is, maintaining a robust yet adaptive base of support while grasping an object and moving it. The challenge of explaining human actions with grasped objects as an embodied cognitive process thus has led to theoretical and statistical models recognizing a system of postural constraints engaging the entire body [133,134]. Recent studies have unveiled a complex network of interactions across various spatial scales during reaching tasks within arm's length. These interactions span broad whole-body postural fluctuations to nuanced movements such as head sway, eye movements and even the minutest-scale photoreceptor activity, as highlighted in the work by Mangalam *et al.* [26]. Reaching further (involving bending at the waist, hips and/or knees) strengthens the coupling between lower- and upper-limb movements [135]. As highlighted by classic studies in the tradition of Nikolai Bernstein, the nervous system adapts and exploits the movement system's degrees of freedom (i.e. the various muscle fibers, bones, tendons and joints capable of moving with minimal interactions) according to the task context. Movement variability allows multi-segment coordination to maintain postural stability and manual performance simultaneously [120,136,137]. Work in this century has shown how the coordination between postural and manual actions varies depending on task demands, practice and constraints on posture [124,125,138,139].

(b) Grasping an object amplifies the sensitivity of posture to movement

Altering the body–environment system to the body+object–environment system alters postural control because the grasped object alters the mechanics of movement of the entire body and thus requires body-wide adjustments to posture and movement. Extending the arm's reach with a grasped object entails longer durations, higher peak velocities, longer deceleration times and more curved trajectories of movements [140,141] than extending the arm alone. Pointing to a target with a grasped object held in an extended arm results in increased variability in the endpoint [140] compared to pointing with the hand alone. Arm extension increases the inertial properties of the arm and amplifies the influence of proximal joint rotations on end-effector control. The accumulation of these disruptions to movement precision might lead to failure to accomplish the intended goal if not for the wellspring of variability in degrees of freedom of movement from the grasping hand and extending down the torso [141,142]. Thus, increased postural sway when moving an object to a point in space (as often happens when tooling) is part of an elegant synergy that ensures comparable levels of stability between the distal tip of the object and the hand, regardless of the object's length.

6. Cascades in posture and manual actions

The idea that adaptive manipulation of objects within our grasp relies on interactions across multiple scales, transcending individual anatomical parts, is not a recent concept [2,143]. The recognition that behaviour involves interactions across scales and extends beyond isolated components has long inspired psychologists studying cognition. These discussions often invoke dynamic processes resembling streams or cascades, where events propagate and converge through branching chain reactions [4,144]. Despite the historical recognition of the interconnectedness of events across scales, integrating numerous degrees of freedom within a fluid framework has historically posed significant challenges for empirical investigations. However, recent advancements in computational analytical tools, honed in various fields over several decades, allow one to model and characterize these cascades effectively [66]. This section delves into this theme, highlighting that haptic and visual information are coordinated throughout the body through cascades of movement. It further demonstrates how the dynamics of cascades can be employed as a formalism to develop theories of cognition that steer clear of computational metaphors.

How can we subject this radical embodied cognitive approach to a rigorous empirical examination? Ethical considerations prevent us from conducting randomized controlled trials that manipulate behaviour by, for instance, removing or incapacitating connective tissue. Nevertheless, we can focus on the precise nature of the body-wide action of connective tissues, which demonstrates abundant interactivity across all measurable scales. Describing connective tissue's nonlinear cross-scale interactions can be accomplished with the geometrical framework known as 'multifractal' (figure 4; [146]). We can intuitively introduce the concept of a multifractal cascade in movement with the example of a relatively uncontroversial relationship between component events of different durations across the timescale of an entire task. For instance, consider reaching for a coffee cup with one hand while standing upright. On an exceedingly fine or short scale, successful task completion hinges on highly dynamic photoreceptor activity (e.g. on the scale of sub-milliseconds) in the retina to stabilize the entire target within the visual field during reaching. At coarser scales (e.g. on the scale of a few milliseconds), the ability to stand and visually fixate the cup relies on bodily sway patterns changing in response to the optic flow in the visual field [123,147]. Interactions among activities across these scales orchestrate the coordination required for maintaining stability across a much longer timescale (e.g. at the scale of a few seconds; [148,149]) to reach for and grasp the cup. All this orchestration is directed against the gravitational force to maintain the motion of the bodily CoM within the stability confines of the base of support [150]. However, events at one temporal scale (say, patterns of bodily sway) do not always stay in their scale. They may bleed into scales beyond where they originated (for example, sway can influence posture throughout the task). Events can begin at one scale and have implications for other events at other scales. For instance, sway can occur over seconds and support the ability of the organism to take steps forward across the next minute, leading to a potentially hours-long search for a misplaced object. The duration and occurrence of these events do not seem to vanish abruptly at a particular scale boundary. Instead, they gradually taper off. We can model this gradual tapering of the size-timescale relationship as a power-law function. Multifractality is little else than a family of power-law functions, and the mathematical relationship among these power laws can provide empirical evidence of the coordination of many-sized events [151,152]. The important point to develop here is that interactions across scales entail power-law functions. In what follows, we hope to make this concept more accessible by pointing to where psychologists have acknowledged the fundamental importance of such power-law relationships.

The concept of interactions among effects across different scales has long been elusive to concise modelling. Although it might seem at odds with emphases on psychological or physiological thresholds, ideas about interactions across scales have always been more flexible than advertised in theoretical models—even for individual neurons [153]. Furthermore, the same long-lived psychophysical traditions promoting thresholds laid the groundwork for expecting 'scale invariance', as in a power-law relationship between stimulus and response [154]. These power-law functions suggested a similar response progression over progressively smaller- or larger-scaled responses, a continuity throughout which the response had an invariant multiplicative relationship to stimulus strength. This invariance across scale—or 'scale invariance of the power law' suggested that the best fitting mathematical model entailed no fixed threshold beyond which response might vanish. The theoretical continuity of this scale-invariant patterning offered a modelling framework for explicitly acknowledging the actual continuity of mechanism across many scales of perceiving-acting systems—across a cascade of large events and small events feeding each other. For instance, the cardiovascular system is not simply a central pump in the chest with a few pipes extending to the periphery; the lungs are not simply smooth sacs for gas exchange, and the digestive system is not simply a long tube. Each of these systems has within it an infinite texture that we only see as we zoom in, with the ever finer structure endowing each surface with a rich capacity to absorb events at multiple scales, from deep inhalations of air to the finest cells composing an immune response or the fragments of a nourishing macromolecule [155]. Power laws have become current concerns for contemporary discourse in social psychology [156,157], neuroscience [158], memory [159] and language use [160].

For our purposes in studying tooling, the scale-invariant continuity of the power law offers a way to model how movement coordination entails a cascading form. Specifically, this entails large-scale intentions enlisting medium-scale synergies, which then intricately recruit fine degrees of freedom. The empirical evidence derived from movement variability consistently suggests that the more extensive and coarse aspects of motion progressively engage increasingly intricate levels of precision [120,136,161]. For instance, the intention to reach engages anticipatory postural adjustments [149,162], then the extension of the arm, followed by the elongation of the fingers. Even at the minutest scales, the fingers maintain their ability to flex, finely adapting the manual grasp subtly. This precision extends to considerations as nuanced as the changing textures of skin or glove material, which can exhibit rippling, slipping or blistering. The intentional manual grasp can depend even on the fine geometric structure of individual fingerprints and how these minuscule hills and valleys channel moisture (e.g. sweat), suggesting a dwindling but never vanishing effect of even the finest points of contact with an object [163]. The relevance of the power law for expressing the progression from coarser to sparser variability has invited the term 'fractal' to evince the understanding that the progression to sparser variability is a type of fractioning of the original larger event.

We understand multifractality by appreciating that one power law does not fit all aspects of the suprapostural system. This is because the size-scale relationship noted above is not limited to one-way trends: large events can unfold rapidly; and small events can unfold slowly [28,66]. The flexibility of interactions among different-sized events abound, yielding whole families of

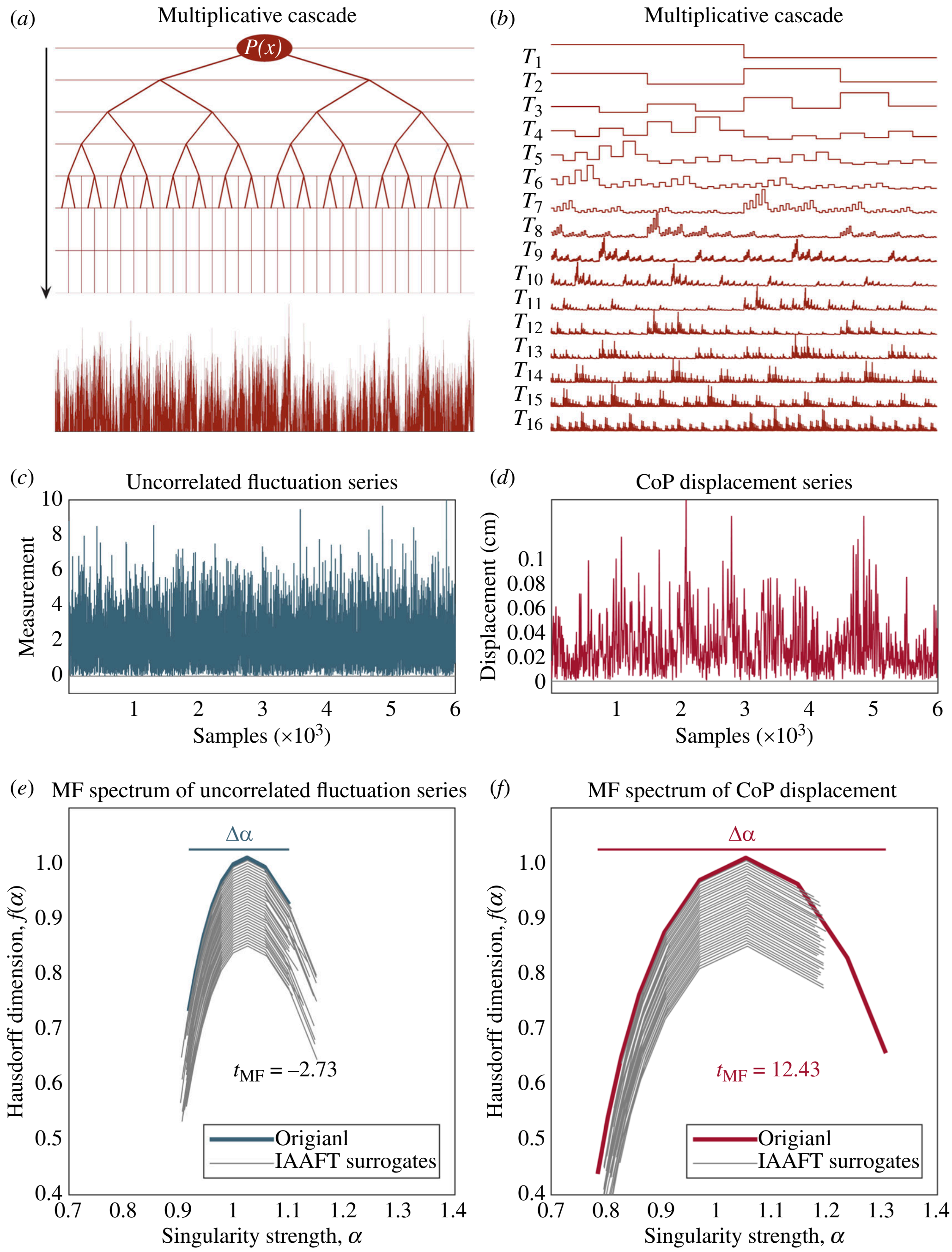

Figure 4. Multifractal analysis allows quantifying the extent of cascade-like nonlinear interactions across scales in the data. (*a*) Illustration of a multiplicative cascade process operating across increasingly refined binary timescales, propelled by a generalized probability density function, $P(x)$. The process commences with the complete time interval and systematically augments the number of intervals through integral powers of two, culminating in $2k$ intervals at time scale T_k. The time series at the bottom embodies a multiplicative cascade phenomenon. In (*b*), a binomial multiplicative cascade emerges as a mathematical construct to elucidate the dispersion of event proportions across progressively diminished sample sizes. The lowermost curve vividly portrays a series of 2^{16} samples representing the cascade's evolution over 16 generations. Each curve is normalized against its peak value and vertically offset by one unit for enhanced visual clarity. We observe a simulated uncorrelated fluctuations series in (*c*). Moving to panel (*d*), we delve into real-world data—the postural CoP displacement series, captured from an individual in a calm stance with a fixed gaze on a distant point. (*e*) The multifractal spectrum (MF) width of uncorrelated fluctuation series and its corresponding iterative amplitude-adjusted Fourier transform (IAAFT) surrogates (totaling $n = 32$). Notably, the absence of significant differences between these spectra widths underlines the lack of nonlinear interactions across scales. The surrogate spectra have been shifted vertically to provide clarity. Shifting to panel (*f*), a distinct pattern emerges. Here, the multifractal spectrum width of the CoP displacement series exhibits a considerable increase compared with the multifractal spectrum widths of its associated IAAFT surrogates ($n = 32$). This conspicuous discrepancy strongly indicates the presence of nonlinear interactions across scales within the data. Again, the surrogate spectra have been shifted vertically to provide clarity. For further details, see Kelty-Stephen & Mangalam, and Kelty-Stephen *et al.* [66,145].

power-law relationships. Thus, a given postural task might exhibit not just one power-law following one power-law exponent but multiple power-laws following multiple exponents. For instance, if we allow participants to stand still, we might find that perturbations in the anteroposterior direction of sway prompt slightly stronger power law form than they do in the mediolateral direction.

Radical embodied cognition has long appealed to cascade-like metaphors, and now we can deploy multifractal modelling as a direct means to test the validity of these metaphors. We can test for the presence and effects of cascades in tooling by estimating the multifractal structure of tooling behaviours and testing whether this structure matters for tooling. If this cascade framework for tooling is empirically supported, a radical embodied cognition perspective can soon become quite specific about the logical structures emerging. If the tooling body experiences a cascade, with task contexts and intentions having large-scale, body-wide implications extending to the movement system's finest scales, then multifractal-type nonlinear cross-scale interactions would be evident. Indeed, the multifractal structure provides compelling evidence of cascading behaviour [151,164,165]. Empirical work has already begun to show that humans' perception of handheld objects' tooling affordances exhibits reliance on multifractal-type nonlinear cross-scale interactions. When we investigate how movements contribute to the tactile perception of object properties while handling an object in hand, it appears logical—or obvious, even—to narrow our focus to the point of contact, such as the mechanoreceptors in the skin. However, the radical embodied cognition perspective made us consider the broader tooling context. When participants, blindfolded and standing on a force plate, used hand movements to perceive object properties, the multifractal-type nonlinear cross-scale interactions of their postural CoP variability predicted their judgements regarding the heaviness and length of the object [166–169]. Despite the object being held in hand rather than in (or under) a foot, the relationship between the feet and the ground surface influenced the effortful touch of the hand. Even in cases where the participant remained still, the same nonlinear cross-scale interactions of the CoP had direct implications for perceiving objects supported by the shoulders, with variations arising depending on whether the individual focused on the entire object or just a part of it [170,171]. These findings prompt us to contemplate the intriguing connection between the hand grasping the object and the feet supporting the body. Similarly, bearded capuchin monkeys, assuming a bipedal posture and using stones weighing at least half their body weight to strike palm nuts on stone anvils, exhibited more precise control over the position of their feet and lower legs during the strike motion compared with their hands and arms [172,173]. It would be interesting to revisit such postural fluctuations with an eye to nonlinear cross-scale interactions.

Between the postural CoP on the support surface and the hand holding the object, the body is rippling with multifractal signatures of nonlinear cross-scale interactions supporting the perception of tooling affordances with that object. When we looked at the electromyography measuring muscular activity, the multifractal signatures of nonlinear cross-scale interactions in the muscular activity of wielding muscles were more predictive of the reported perceived length of the grasped object than was the magnitude of measured muscular activity alone [174,175]. Nonlinear cross-scale interactions spread across the body to perceive affordances; for instance, participants' heads display subtle, cascading swaying movements that critically impact their ability to integrate visual feedback [27]. We can train perception of tooling affordances through wielding by the hand or even by the foot, and the training of either limb can transfer to the other. The signatures of nonlinear cross-scale interactions at each limb predict how well the trained limb exploits object parameters and how well this training transfers to the other limb [176].

In summary, perceiving what a moving object affords permeates the entire organism. It is a global response encompassing the entire body's movement [167,168]. To test this idea, we recruited adult human participants to judge the heaviness of handheld objects, recording both their verbal judgements and a full-body motion-capture marker set. We estimated the multifractal structure for each marker position. Using a rudimentary network analysis of all pairwise relationships between each pair of marker positions, we tested for the exchange of multifractal fluctuations across various anatomical locations, from one marker location to each of the others. This analysis revealed the spread of nonlinear cross-scale interactions from one degree of freedom to another as participants engaged in perceptual exploration of the potential tool in hand [167,168]. The body-wide spread of nonlinear cross-scale interactions laid bare a fascinating set of relationships supporting the perception of tooling affordances. For instance, the wielded object and arm interacted across multiple scales, mutually enhancing each other's contribution. Exploring how we can grasp and wield an object leads that object to absorb multifractal fluctuations of both the arm and the hand. Then, the multifractal fluctuations of that object reverberate back up the hand and arm and through the body. Thus, multifractal movement patterns propagate from the torso, the upper arm and the forearm to the object and vice versa, influencing the forearm, the upper arm and the torso. Moreover, beyond these interconnected relationships within the upper body, an increase in multifractality within the postural CoP predicted subsequent improvements in perceptual accuracy (figure 5). These findings exemplify why it is crucial to envision the body+object system as constantly adapting its configuration and to consider the waxing and waning of cascading movement patterns across the body to facilitate the perception of affordances [66].

Multifractal cascades are not exclusive to bipedal organisms [177–179]. Nevertheless, it becomes evident that once bipedalism is in place, multifractal cascades actively support upright human bodies' engagement with their environment in distinctive ways not shared with other primates [28]. Bipedalism serves as an evolutionarily novel constraint that would press the generic lawfulness of cascades into a novel behavioural form [180]. Bipedalism introduces a fresh dimension to the cascades that characterize the body-wide exchange of multifractal fluctuations in organisms [177–179]. Consequently, perhaps tool use flourishes in humans in more elaborate forms and greater frequency than in non-human primates in part because the body-wide multifractal cascades are no longer confined solely to the forelimbs constrained to the substrate. Bipedalism bestows multifractal cascades with a new constraint, perhaps facilitating increasingly creative solutions to interact with distal surfaces and objects in the environment. An important challenge for the field is determining how dynamic cascades associated with infants' assumption of bipedal stance and locomotion participate in their developing allocentric spatial perception and sense of agency and, quite soon after, becoming 'obligate tool-users'.

7. Concluding remarks

We have marshalled evidence that humans' effective agency with handheld tools using allocentric frames of reference can directly or indirectly relate to our bipedalism, evolutionarily, developmentally and moment-to-moment. Do these findings support a radical embodied conception of tooling, and would this conception help novel and productive research directions?

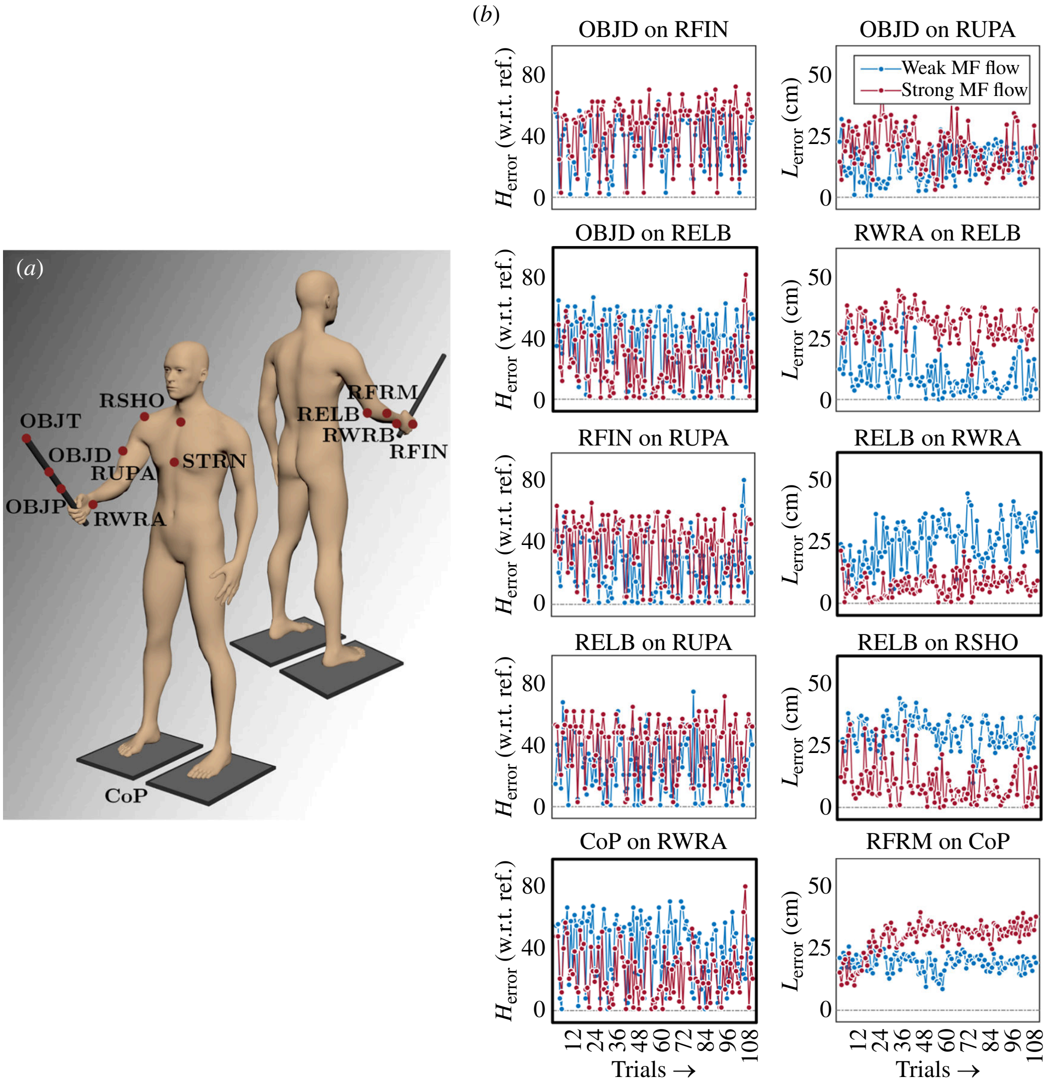

Figure 5. The dynamic touch, facilitated by the intricate flow of multifractal fluctuations across the body, plays a pivotal role in perceiving the weight and length of handheld objects. (*a*) In a study investigating this phenomenon [168], participants wielded weighted dowels for 5 s while standing on force plates recording their ground reaction forces, with a motion tracking system tracking movement fluctuations across the body. The task involved vocalizing a numerical judgement of the object's heaviness (e.g. 50 or 200, indicating half or twice the weight of a reference object) and adjusting a marker along a string-pulley arrangement to express their perception of its length. With this arrangement, we captured the nuanced fluctuations in the movement of various body parts and the postural CoP, using multifractal analysis followed by network modelling. Marker placements: OBJP: tip of the object; OBJD: 30 cm from the object's distal end; OBJP: 30 cm from the object's proximal end; RFIN: just below the middle knuckle on the right hand; RWRA: extended from the thumb side using a wrist bar; RWRB: extended from the little finger side using a wrist bar; RFRM: outside of the lower arm; RELB: bony prominence outside of the elbow joint; RUPA: outside of the upper arm; RSHO: bony prominence on top of the right shoulder; CLAV: top of the breast bone; STRN: base of the breast bone. (*b*) A comparative exploration of perceptual accuracy unveiled the intriguing interplay of multifractal fluctuations across distinct body segments. For participants showcasing either weak or strong flows of multifractal fluctuations between these segments, the impact on perceived heaviness (H_{error}) and perceived length (L_{error}) was striking. The strong inter-relationship between the object's dynamics and the body's responses was evident in the strong effects of object dynamics on the forearm and of postural sway on the wrist. This robust connection led to a noteworthy reduction in H_{error} (as highlighted in the bold panels on the left). Conversely, other inter-relationship effects increased H_{error}. Moreover, the pronounced influence of the elbow dynamics on the wrist and shoulder dynamics exhibited a discernible decrease in L_{error} (as emphasized in the bold panels on the right). Conversely, the remaining interrelation effects increased L_{error}.

We think the answer is 'yes'. Taken together, recognition of humans' suprapostural dexterity and recognition that intentional actions can be conceptualized and analysed as multifractal cascades involving the entire body open a new direction of research and thought about humans' skilled manual actions with tools. A fuller awareness of the rich wellspring of activity in the movement system should advance our understanding of embodied cognition and its applicability to human concerns. Investigating how patterns of whole-body coordination support suprapostural activities, such as tooling, could lead to novel research avenues rooted in the traditions of Gibsonian ecological psychology, Bernsteinian movement science, and the contemporary framework of radical embodied cognition. Such work could take comparative, developmental or applied directions and contribute to allied fields like robotics. Furthermore, this should propel our comprehension of the spectrum of actions involving handling objects, encompassing tooling within contemporary societies and the historical narrative of our forebears and predecessors.

Ethics. This work did not require ethical approval from a human subject or animal welfare committee.

Data accessibility. Data sharing does not apply to this article as no new data were created or analysed in this study.

Declaration of AI use. We have not used AI-assisted technologies in creating this article.

Authors' contributions. D.M.F.: conceptualization, project administration, writing—original draft, writing—review and editing; D.G.K.-S.: visualization, writing—original draft, writing—review and editing; M.M.: conceptualization, visualization, writing—original draft, writing—review and editing.

All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

Conflict of interest declaration. We declare we have no competing interests.

Funding. This work was supported by the Center for Research in Human Movement Variability at the University of Nebraska at Omaha, funded by the NIH award P20GM109090.

Endnotes

[1]A trait that originated through selection for a given function but that has subsequently taken on other functions; *sensu* Gould & Vrba [37].

[2]Stoffregen [75] formally defined an affordance as the following: Let W_{pq} (e.g. a person-climbing-stairs system) = $j(X_p, Z_q)$ be composed of different things Z (e.g. person) and X (e.g. stairs). Let p be a property of X and q be a property of Z. The relationship between p and q, p/q, defines a higher-order property (i.e. a property of the animal–environment system), h. Then h is said to be an affordance of W_{pq} if and only if (i) $W_{pq} = (X_p, Z_q)$ possesses h; and (ii) neither Z nor X possesses h.

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