

Adaptation or exaptation? The case of the human hand

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A controversy of relevance to the study of biological form involves the concept of adaptation. This controversy is illustrated by the structure and function of the human hand. A review of the principal definitions of adaptation points to two main problems: (1) they are qualitative and make reference to the whole structure (or substructural feature) and (2) they are based on the idea of natural selection as a moulding factor. The first problem would be solved by a definition that encompasses quantitative measures of the effects of selection, drawing on new advances in the comparative method. The second problem is deeper and presents greater conceptual difficulties. I will argue that the idea of natural selection as a moulding factor depends on the notion of a genetic program for development. But regarding the hand, experimental evidence on limb development challenges the idea of a genetic program for skeletal pattern formation, undermining a simple application of standard adaptationist concepts. These considerations lead to a revised definition of adaptation and interpretation of the evolutionary determinants of the hand's form.

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1. Introduction

Is the hand an adaptation? Probably the intuitive answer to this question is a 'yes'. But in trying to justify the answer we run into a long-standing controversy about how to define an adaptation, and what seemed a simple question turns out to be a complex, less intuitive issue. The problem is that there is no unique and uncontroversial definition for classifying a structure as an adaptation, but several of them have been proposed. Consequently, a structure could be classified as an adaptation or not depending on the definition we choose.

Here the principal definitions of adaptation and exaptation will be analysed. Subsequently, these definitions will be used to classify the hand. In doing this, two problems of these definitions will be pointed out: (1) all these definitions are qualitative and do not reflect recent improvements in the comparative method and (2) the role of natural selection as a creative factor is questioned by new findings in developmental biology. A brief retrospective view will reveal the existence of

two frameworks in the study of biological form (externalist and internalist) and how the idea of natural selection as a creative factor – and consequently the validation of the externalist framework – depends on the idea of the existence of a genetic programme for development. These two frameworks will be contrasted in the example of tetrapod limb development. In the final section, an answer to the proposed question will be provided.

2. Adaptation and exaptation

A review of the literature reveals the existence of two research programmes underlying the proposed definitions of adaptation: (1) attempts to explain 'phenotypic prevalence' (i.e. why certain structures have become established) and (2) attempts to explain organic form (i.e. why structures look the way they do) (e.g. Gould and Vrba 1982; Fisher 1985; Coddington 1988; Thornhill 1990; Baum and Larson 1991; Harvey and Pagel 1991; Lauder *et al.* 1993; Reeve and Sherman 1993; Sober 1984;

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Amundson 1996; Griffiths 1996; Autum *et al.* 2002; Bock 2003).¹

These two projects are not identical, as has been stressed by several authors (e.g. Darwin 1859; Gould and Vrba 1982; Williams 1966; Gould 2002). There are structures useful for organisms that were not originated for the biological role they actually perform. In these cases, natural selection could explain their persistence, but their current biological role does not explain their morphology.

A common example to illustrate this point pertains to the morphology of snails. Snails that grow by coiling a tube around an axis generate a cylindrical space along this axis. This space (called an umbilicus) is usually filled with calcite, but in some species – especially among the land snails – it is open and is used as a brooding chamber to protect the eggs (Lindberg and Dobbarten 1981, cited in Gould 1997). The umbilicus is useful (fit) as a brooding chamber and probably this role has favoured its persistence; however, its usefulness is not the explanation of its form. The reason for the umbilicus resides in the way snail shells develop; it has a mathematical explanation.

Regarding the hand, the pentadactyl pattern is present in species with very different lifestyles. Thus, while this pattern seems useful for several locomotory and manipulative behaviours and these roles have probably favoured its presence in some taxa, they do not explain this pattern. Another example is the thin digit of *Daubentonia madagascariensis*. This lemur uses its thin middle digit to pick out insects from small holes in trees. This role has probably favoured its persistence but would not explain its form; in fact, thin digits seem to be a generic property of certain mechanisms of tetrapod limb development (Miura *et al.* 2006).

In a post-Modern Synthesis re-evaluation of the concept of adaptation, Williams (1966) pointed out the importance of distinguishing between those structures useful for an organism because they have been built up by natural selection to meet contemporaneous functional demands, and those accidentally useful to an organism, i.e. not moulded by natural selection for their current role. He restricted the term ‘adaptation’ to the first type and referred to the second as ‘fortuitous effects’. Thus, a structure is an adaptation if (1) it enhances organismal performance – the criterion of *current utility* and (2) it

was built by natural selection for the role it currently performs – the *historical criterion*.²

To Williams (1966), a definition of adaptation must address the aims of both aforementioned programmes, i.e. to explain both phenotypic existence and form. Classifying a structure as an adaptation implies that it exists because it is maintained by natural selection and has been built to perform its current role, which implies that its form can be explained in functional terms.

Gould and Vrba (1982) addressed this issue by devising terminology focused exclusively on explaining organic form. They noted the existence of structures useful currently for an organism and not built for their present biological role (i.e. they do not meet the historical criterion), similar to some cases considered by Williams, and even earlier by Darwin (1859). Bock (1980) also sought a definition of adaptation useful for explaining organic form. Based on his non-historical definition, structures are adaptations if they have ‘properties of form and function (*sensu* Bock and von Wahlert 1965) which permit the organism to maintain successfully the synergy (*sensu* Bock and von Wahlert 1965) between a biological role of that feature and a stated selection force’ (Bock 1980 p 221). Thus, to classify a structure as an adaptation is to demonstrate that its form is currently useful for the organism, no matter how it arose: ‘it is immaterial how particular adaptations, be they survival or reproductive features, come into being... A feature is an adaptation with respect to a particular selective agent regardless of how it came into being...’ (Bock 2003 p 238).

Gould and Vrba (1982) rejected calling these structures adaptations, since if the origin of a structure is not related to the role it performs, its form cannot be exclusively explained in functional terms.³ They introduced the term ‘exaptation’ to describe such cases of disconnection between form and current function. Exaptations could be partially or not moulded at all to meet present functional demands. The latter is the case for the umbilicus of the snail shell, and the authors appropriated the term ‘spandrels’ for such structures (*see* also Gould and Lewontin 1979). To

¹ I will focus specially on Gould and Vrba’s discussion. I will also focus on the comparative approach developed to explain form. For optimality approaches more directly related to phenotype persistence projects see, e.g. Hansen (1997) and Orzack and Sober (2001). For philosophical aspects related to the term, such as the problem of relativity of explanation or the multifarious nature of adaptationism, *see* e.g. Amundson (2001), Sansom (2003) and Godfrey-Smith (2001). *See* Fodor and Piattelli-Palmarini (2010) for an extensive and recent analysis. For a physiological concept of the term *see* Dressino (2005).

² For Sober (1984) it is sufficient that the structure accomplishes the historical criterion, irrespective of its current usefulness. He states that: ‘Adaptation and ‘fitness’ (adaptedness) are complementary concepts. The former looks to the past, reflecting the kind of history that a trait has had. The latter looks to the future, indicating the chances that organisms have for survival and reproductive success. These retrospective and prospective concepts are mutually independent. An adaptation [according to the historical criterion] may cause problems for the organisms that have it; a changed environment may mean that an adaptation is no longer advantageous’ (Sober 1984 p 210; bracketed text mine).

³ They restricted Williams’ definition even more so that it was not sufficient that a structure has been moulded by selection for its current role, it must have been moulded exclusively under the current selective regime (the criterion of historical genesis).

reiterate, if a form is an exaptation, its current role does not explain all of its distinctive features.

'Pre-adaptation' was an earlier term used for structures already existent that could be co-opted for a new biological role. However, this term was controversial because it also denoted some foreordination, a purposive directional change. Gould and Vrba's term exaptation was proposed to resolve the problem by dissociation from any teleological implication.

While Gould and Vrba (1982) stressed the importance of incorporating an historical component into a definition of adaptation useful for morphological studies, researchers interested in the explanation of phenotype existence advocated a non-historical definition. Certainly, as Reeve and Sherman (1993) strongly argued, the past history of a trait is irrelevant for ascertaining why a structure is now spreading through the population.

Gould and Vrba's historical definition of adaptation led to the incorporation of phylogenetic relationships for testing adaptative hypotheses (Blackburn 2002). A general procedure consists of constructing a phylogenetic tree based on molecular or morphological data and then plotting on the tree the trait to be tested and the functional external demand. According to the *derived trait concept* (Reeve and Sherman 1993), a trait would be an adaptation if it is a derived trait (i.e. apomorphic of a clade) and it is concomitant with the functional external demand for which it is useful.

Subsequently, the methodologies for incorporating phylogenetic relationships into comparative analyses (called the 'new comparative method') underwent great improvement, accompanied by important discussions about its significance

in the study of adaptation (Frumhoff and Reeve 1994; Leroi *et al.* 1994; Losos and Miles 1994; Martins 2000).

3. Classifying the hand: A look from outside

Following the criterion of current utility, the hand would be classified as an adaptation since it enhances the performance of the relevant species; an image of the disadvantage of malformed hands readily comes to mind. Following the historical criterion in which a structure is an adaptation if it has been moulded to meet specific functional demands, the hand would be also classified as an adaptation, since different primate species show some morphological differences related to the performance of special grips. Humans, baboons and mandrills present several specific morphological features that enable some special grips, e.g. 'precision grips' when an object is held by the fingertips, and 'power grips', where an object is forcefully grasped by fingers and palm (figure 1). For example, a proportionately long thumb and shorter fingers – in contrast to the relatively short and weak thumb in other primates – is suggested to be one of the features that allow the performance of these grips (note that no unique feature is responsible for such high precision grips, as several anatomical characteristics act conjointly; Marzke and Marzke 2000).

The use of phylogenetic relationships (based on molecular and morphological data) and morphological datasets of the hands of extant and fossil species has allowed the reconstruction of the evolution of the hominin hand (Tocheri *et al.* 2008). This work has shown that features

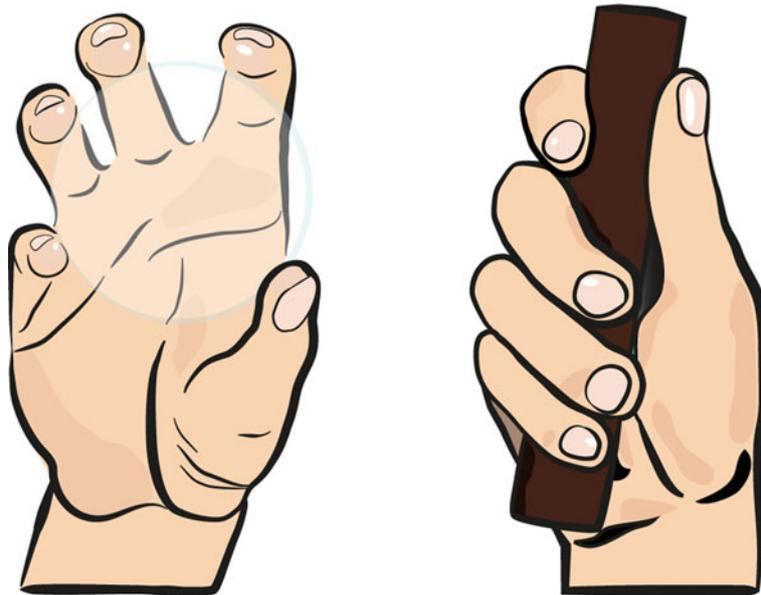


Figure 1. A precision grip (left) and a power grip (right) (based on Napier 1956).

most likely present in a hypothetical *Pan-Homo*, the last common ancestor, are retained in some hominid genera (*Australopithecus*, *Paranthropus*/early *Homo* and *Homo floresiensis*) and that the modern hand of Neanderthals and humans did not evolve until 2.5 or 1.5 Mya and could represent adaptations to more complex tool-related manipulative behaviours.

A recent biomechanical study suggests that some of the derived characteristic of the radial digits of the human hand (long robust thumbs, relatively larger joint surfaces and hypertrophic thenar muscles) are suited for producing strong gripping forces and for tolerating higher joint stress, and could have evolved in the lineage *Homo* in relation to tool making and tool use. Marzke and Marzke (2000) offer a review of the different techniques that can be used to study the adaptiveness of the hand for such purposes (for more recent quantitative analyses, see Marzke *et al.* 2010; Tocheri *et al.* 2003; Tocheri *et al.* 2005; Organ *et al.* 2010). Other studies from the field of anatomy have shown that some subtleties of the movements of the human hand elude a qualitative characterization and require a detailed mathematical description (Hutchison and Hutchison 2010).

Note that tool-making and tool-using capabilities of the hand were also well suited later on to perform a great variety of roles despite the fact that they did not evolve to perform them. In such cases, these features would be adaptations to tool making and tool use, but exaptations for writing or playing guitar.

Despite the fact that some features of the hand such as the thumb/index ratio or the broad apical tufts of the distal phalanges, among others, have a functional meaning regarding their role in the performance of special grips and high manipulative behaviours related to tool making and tool use, other remarkable features, like its pentadactyl pattern, cannot be explained by locomotor or manipulative requirements. The pentadactyl pattern is not a defining feature of primates' hands but is common to other species of mammals (e.g. dogs or tigers) and some reptiles and amphibians. Thus, the five fingers of the hand are very useful for manipulation, but this biological function cannot explain this pattern.

This is the reason why Gould and Vrba (1982) incorporated the criterion of historical genesis to the definition of adaptation along with the current utility criterion. According to this definition the structure should be not just be moulded, but also originated, by its present role. Only in such cases would the functional role of the structure explain its *overall* morphology.

Since the autopod in its pentadactyl form is a novelty⁴ of tetrapods that did not originate to manipulate objects, then,

⁴ It is generally accepted that the autopod is a novelty of tetrapods (e.g. Wagner and Chiu 2001); however, some authors have been argued that it is a structure derived from fins rays (Boisvert *et al.* 2008).

according to Gould and Vrba's terminology, the human hand is not an adaptation but an exaptation. This is the case irrespective of how much evolution within the hominid lineage led to refinements that we associate with the human version.

Gould and Vrba's definition of adaptation overcomes the difficulty of characterizing this phenomenon by default, since there is probably no structure that truly fits it: 'If ear bones and gill arches are regarded as the same trait ... then ear bones are exaptations ... because the bones no longer function to support gills. Indeed, nearly every trait is an exaptation if we go back far enough in time' (Reeve and Sherman 1993 p 3). That is, all structures would be exaptations, and adaptations would simply not exist according to this definition.

It is therefore not correct to refer to the hand or to some of its sub-structures as adaptations, because its *overall* morphology (in contrast to some of its refinements) cannot be explained exclusively in functional terms. Part of the controversy generated by Gould and Vrba's definition of adaptation could be solved if, instead of referring to the whole hand or some of its substructures, the term is used to refer to some of its *features* as being adaptations for special grips. But there is still a problem. The differences among species of some features such as the width of distal phalanges or the area of the saddle-shape joint of the trapezium will be small. Most likely their sizes and shapes will overlap. Only appropriate statistical tests can determine whether these partitioned morphological features are significantly different among species and provide a quantitative measure of the percentage of variation of the feature related to a specific functional role (Tocheri *et al.* 2003; Linde *et al.* 2004; Tocheri *et al.* 2005; Marzke *et al.* 2010; Organ *et al.* 2010). However, currently available definitions are *qualitative* and refer to a structure or to a feature as a whole.

The formulation of a definition that encompasses the quantitative aspect would resolve this problem.⁵ However, there is still another, deeper problem with current definitions of adaptation: all of them are based on the questionable idea that natural selection is a moulding, creative factor.

4. Natural selection as a creative factor: A brief retrospective view

The form–function relation was recognized long before the formulation of any theory of evolution (Bock and Wahlert 1965). During the pre-evolutionary theory era, the

⁵ Note that the proposed question is ill-formulated. As stressed by Bock and Wahlert (1965) it is not correct to say that some structure is an adaptation (or an exaptation) without specifying its functional role. It can be added that it is also required to refer not to the whole structure (or feature) but to the percentage of its variation related to the specific functional role.

concept of an adaptation referred to these form–function relations, and it was characterized as follows: a feature that fits the environmental demands of the organism’s habitat. The term was unequivocal because it referred to the observed pattern (i.e. it did not imply any specific originating mechanism). Subsequent controversies about adaptation are generally related to the mechanisms proposed for its existence and about its central role in the evolutionary process.

At the beginning of the 19th century, Natural Theologists formulated the argument from design, proposing God as the explanation for the existence of form–function relations. Later in the century, natural selection replaced God as the mechanism for their existence: ‘When the ‘hand of the creator’ was replaced in the explanatory scheme by ‘natural selection’, it permitted incorporating most of the natural theology literature on living organisms almost unchanged into evolutionary biology’ (Mayr 1982 p 105). That is, both represent an ‘externalist’ approach for the study of biological organization, in which an external agency has given form to organisms and where adaptations (form–function relations) follow from this.

Darwin’s theory was not initially accepted by scholars. But at that time the debate was not evolution *versus* creation, as wrongly propagated during the 20th century⁶ (Amundson 1998), but was about the inadequacy of the selection theory to explain certain observations. In a review of the situation, Kellogg (1908) wrote:

Darwinism...is not synonymous with organic evolution, nor with the theory of descent (which two phases are used by the biologist practically synonymously). Therefore when one reads of the death-bed of Darwinism, it is not of the death-bed of organic evolution or of the theory of descent that one is reading. While many reputable biologists to-day strongly doubt the commonly reputed effectiveness of the Darwinian selection factors to explain descent... practically no naturalists of position and recognised attainment doubt the theory of descent (p 3).

But at the beginning of the 20th century a group of scientists agreed to elevate natural selection to the exclusive directing force of evolution, by the formulation of the so-called Modern Synthesis (Mayr 1993). As stressed by Gould (2002), for natural selection – a filtering process – to be a

creative factor, the generation of variation has to present specific characteristics:

Darwin reasoned that natural selection can only play such a role if evolution obeys two crucial conditions: (1) if nothing about the provision of raw materials – that is, the sources of variation – imparts direction to evolutionary change; and (2) if change occurs by a long and insensible series of intermediary steps, each superintended by natural selection – so that ‘creativity’ or ‘direction’ can arise by the summation of increments (Gould 2002 p 140).

Organisms were conceived as assemblages of traits that vary more or less independently, arbitrarily (not directed to meet a functional demand) and in small steps (Gould 1982). This matched with the idea of the genetic programme (Schrödinger 1945), which developed into the notion that every trait was encoded by more or less independent groups of genes (‘adaptative gene complexes’), each with small effects on the phenotype (Depew and Weber 1996). Owing to the high combinatorial power of the DNA, it was also supposed that any form could be generated (isometric variation), and that natural selection had moulded every trait to meet the external selective demands.

Criticisms of the power of natural selection to mould organic form arose again at the end of the 1970s by the publication of the well-known paper ‘The Spandrels of San Marco and the Panglossian Paradigm: A Critique of the Adaptationist Programme’ (Gould and Lewontin 1979). The authors criticized the poor scientific rigor of many evolutionary studies and the assumption of considering organisms as assemblages of traits that could be moulded independently by natural selection without any limits. They asserted in contrast that organisms are complex integrative systems, less malleable by natural selection than had been previously assumed.

The architecture of the genome is very complex. The hierarchical organization of the genome implies that some regulatory genes, upstream in the genetic networks, could produce large changes at the phenotypic level which would contradict gradualism (‘macromutations,’ Chouard 2010). The presence of highly integrated modules implies that changes in one gene will affect several traits at once (Wagner and Zhang 2011), which would contradict the conception of organisms as aggregates of discrete traits. ‘Genetic assimilation’ (when a environmentally induced phenotype is later implemented genetically) (Waddington 1953) and ‘directed mutation’ (mechanisms possessed by bacteria to generate variation only at specific sites of the genome in response to environmental change) in multicellular and unicellular organisms, respectively (Wright 1997), contradict the non-directedness of variation asserted by the Modern Synthesis.

⁶ ‘The common image of 19th-century transcendentalism as an Argument from Design and as scientifically vacuous reflects the functionalist perspective of modern neo Darwinism...It makes a bogeyman of historical biological structuralism, presenting it as the very antithesis of scientific evolutionary thought’ (Amundson 1998 p 174). According to the author, the association of structuralism with creationism was a trick carried out by some neo Darwinists to throw out the potential scientific alternative to Darwinism.

After the fall of Gould and Lewontin's Dr Pangloss⁷ and attempts by adaptationists to partly restore him (Pigliucci and Kaplan 2000), new findings and concepts have been added to the Modern Synthesis framework, resulting in the Extended Synthesis (Pigliucci and Müller 2010). That is, the externalist approach to the study of form still prevails where natural selection is considered the organizing principle of organic form, with the recognition that there are some limits (constraints) on it. Although natural selection was thus divested of some of its supposed moulding power, the study of adaptations still occupies a central role.

While the importance of constraints in evolutionary phenomena is now generally recognized, they are not interpreted by most advocates of the extended Synthesis as a new causative factor in the study of organic form; they represent, rather, a set of limits to possible change (Amundson 1994). For example, a reduction to three digits has occurred in the forelimb during the evolution of birds. Their ancestry in the dinosaurs, where the digit I, II, III pattern is uncontroversially present, suggests that the anteriormost digit of birds is also digit I; IV and V have been lost. However, studies on limb development indicate that when digit reduction occurs the first digit to be lost is the digit I, followed by digit V (Alberch and Gale 1983). This has been traditionally interpreted as a developmental constraint in tetrapods. A change in the 'digit code' during theropod evolution where precartilaginous condensations II, III and IV would develop later in ontogeny into digits I, II and III has been proposed as a solution to resolve this puzzle (Wagner and Gauthier 1999). According to this interpretation, the functional demands would have overcome the developmental constraint in dinosaurs and direct the morphological changes in birds. Here developmental studies are integrated into the study of evolution to set the limits to the possible ways of changing a structure, but the

mechanism by which digits are generated (*see below*) seems to be irrelevant as a causative factor.

But the integration of development into evolutionary biology also has a different, parallel history (Newman 2003a). This alternative approach to the study of organic form, often infused with physical ideas, has been marginalized by the governing paradigm, but never disconfirmed. Its roots can be traced back to Lamarck, the morphologists of the 18–19th centuries such as Goethe, Cuvier, Geoffroy St. Hilaire, and Richard Owen, and later to the embryologist Hans Driesch and the geneticist William Bateson among others (Webster and Goodwin 1982; Goodwin 1994; Newman 2007; Newman and Bhat 2011).

The alternative track posits the existence of generative principles underlying the organization of living beings. These organizing principles represent internal processes of form generation and transformation. Instead, the mainstream perspective on the evolution of form has been dominated by the idea of a genetic programme for development, i.e. that form is encoded in genes (Davidson *et al.* 2002; Carroll 2005). This conceptualization of development makes the search for organizing principles a fruitless enterprise. If form is encoded in the genes, it is essentially arbitrary, and biological order is contingent. In this case, evolutionary biology becomes essentially a historical narrative and any regularity across taxa would be interpreted, not as evidence for the existence of natural laws – as it is the case in other sciences – but as historical contingencies now recorded in genes. The *arbitrariness of form* embodied in the idea of a genetic programme for development rules out the existence of an internal *cause* of biological organization and thus represents the ultimate form of externalism in which natural selection is the organizing factor of organic form.

In the next section I will contrast two models on limb development in their interpretation of experimental evidence that questions the idea of a genetic programme for limb development.

5. Limb development: A look from inside

Structures that remain unchanged across taxa and which cannot be explained in functional terms do not occupy a central role in the externalist approach. Contrarily, from the internalist approach invariant properties among taxa occupy a central role because these regularities would be indicative of the existence of underlining principles. In the following I summarize experimental evidence relating to the formation of the pentadactyl pattern, or more precisely, for the quasi-periodic arrangement of skeletal elements of all tetrapod limbs. I then contrast accounts of contending models for the process.

The limb bud is formed by a tissue of loosely associated mesenchymal cells (mesoblast) covered by an epithelial tissue. Mesenchymal cells are separated from each other by

⁷ Gould and Lewontin (1979) characterized as 'Panglossian' the common view that natural selection was a powerful force that had been optimized every organism's trait. This term makes allusion to Dr Pangloss, a character in Voltaire's *Candide*. The authors expressed Dr Pangloss's optimism citing a paragraph where he explains to Candide why venereal illness exists:

It is indispensable in this best of worlds. For it Columbus, when visiting the West Indies, had not caught this disease, which poisons the source of generation, which frequently even hinders generation, and is clearly opposed to the great end of Nature, we should have neither chocolate nor cochineal

and they add: 'The adaptationist programme is truly Panglossian. Our world may not be good in abstract sense, but it is the very best we could have' (Gould and Lewontin 1979 p 585).

Most of the controversy discussed until here could be understood as against the Panglossian view of nature, i.e. against the description of natural selection as an 'engineer' rather than a 'tinkerer' that does not remodel extant things to get perfect designs but works on what it is already present, using old structures to perform new roles (Jacob 1977)

the extracellular matrix, a medium composed of polysaccharides and fibrous proteins. The formation of cartilaginous templates, which are subsequently replaced by bone and form the limb skeleton, is preceded by the formation of mesenchymal condensations. These precartilaginous condensations are formed when mesenchymal cells produce and secrete extracellular matrix proteins that mediate cell–matrix adhesion (e.g. fibronectin) and consequently trap cells. The initial aggregations are reinforced by the expression of cell–cell adhesive proteins. Cells within these condensations differentiate into chondrocytes (cartilage cells). The mesenchymal cells that are not incorporated into condensations differentiate into fibroblasts (cells of soft connective tissue) or die off by apoptosis (reviewed in Newman and Bhat 2007).

Because all the mesenchymal cells can produce both extracellular and cell–cell adhesive proteins, and thus, all of them can differentiate into chondrocytes, the existence of some mechanism for generating the skeletal pattern is needed. The idea of a genetic programme for limb patterning is represented by the ‘positional information’ theory developed by Wolpert (1969). According to this concept, certain diffusible molecules specify the spatial three dimensional positions of each cell in the limb field, and the skeletal pattern emerges because this ‘positional information’ is translated by cells according to a genetic programme that activates the corresponding developmental pathway and switch them – via a transcriptional mechanism – into chondrocytes, fibroblasts or apoptotic cells. In other words, the genetic programme for limb development must contain a complete representation of the developmental fate of every cell in the limb bud.

An alternative view suggests that the pattern of precartilaginous condensations is not pre-specified as in the positional information theory, but it emerges dynamically during limb outgrowth by means of interactions between mesenchymal cells (Newman and Frisch 1979; Newman 1988). If each cell can produce and secrete a morphogen (activator) that stimulates the production of extracellular matrix proteins by itself (autocrine induction) and by surrounding cells (paracrine induction), triggering the generation of precartilaginous condensations and if, at the same time, each cell is also capable of producing and secreting a second morphogen (inhibitor) that represses the activator and consequently, the generation of precartilaginous condensations; if the activator also induces the production of its inhibitory morphogen, and if these morphogens diffuse at different rates, reaction-diffusion models, such as those first described in detail by Turing (1952), predict that homogeneity is an unstable state and that patterns would emerge spontaneously in these systems. In this framework, limb bud mesenchyme is not a passive entity that would need a genetic programme for generating a pattern, but it is an active entity, an excitable medium with the inherent capacity of generating patterns

spontaneously by its intrinsic physico-chemical properties (Goodwin 1994; Newman 2003b).

Some molecules that fit the characteristics required for reaction-diffusion⁸ processes have been identified in the limb bud, and a core reaction-diffusion cartilage patterning network capable of reproducing skeletal patterns has been proposed (Zhu *et al.* 2010).

Some remarkable developmental findings strongly argue against the idea of a genetic programme for skeletal patterning formation. When a ‘recombinant limb bud’ is constructed by packing randomized limb bud mesenchymal cells into a new ectodermal jacket and transplanting it to the embryo flank, clearly recognizable limb-like skeletal patterns are formed (figure 2). More strikingly, these limb-like structures are formed even when recombinants are constructed from mesenchymal cells of different species (Pautou 1973).

These limb-like structures are formed in the absence of any positional information map formed by monotonic gradients of morphogens. In particular, any such gradients would be entirely disrupted when mesenchymal cells are dissociated and gene expression patterns are altered (Ros *et al.* 1994), confirming that limb bud mesenchyme is capable of producing quasi-periodic arrangements of skeletal elements spontaneously by virtue of its intrinsic physical and cellular-biochemical properties.

The limb-like structures of recombinant limb buds represent the commonality underlying limb pattern diversity; they represent a *generic* form of tetrapod limbs (Newman 1988) and the dynamical laws describing their generation represent its organizing principle (Zhu *et al.* 2010). As it is shown in figure 2, these generic forms do not exhibit polarity (i.e. the parallel elements are similar each other) and the number of proximodistal elements is unusual. Here the monotonic gradients of signalling molecules and Hox genes come into play: they do not *generate* skeletal patterns (they do not specify where to form cartilage primordia as in the positional information theory), but they may stabilize and fine tune otherwise equivalent elements which are generated by a common mechanism of cartilage patterning.

Contrarily, in the positional information theory there is not a common mechanism that lays down a whole cartilage pattern which is subsequently customized to form specific bone shapes, but each bone would be formed individually by a subprogramme that translates a specific set of morphogens (their concentrations and combinations, and in some cases also the exposure times to them) into a specific bone shape, so each bone is non-equivalent from its inception. In the positional information model the invariant property of skeletal limb patterns (the quasi-periodic

⁸ In biology, reaction-diffusion models are called LALI (local selfactivation-lateral inhibition) models (Meinhardt and Gierer 2000).

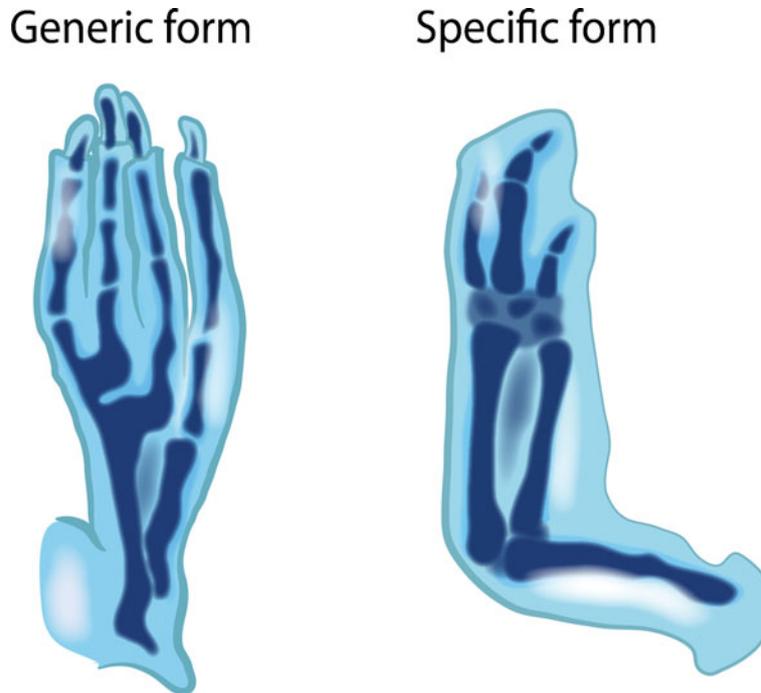


Figure 2. A heterospecific (chick and duck) recombinant limb bud (left) would represent a generic form of the limb field, showing self-organizational capacity of mesenchymal cells to form quasi-periodic arrangement of skeletal bones in absence of a ‘positional information’ map. The forelimb of a chick (right) as an example of a specific skeletal pattern derived from the regulation and stabilization of a self-organizing process (the recombinant limb is redrawn from Pautou 1973).

arrangement of bone elements) is a fortuitous similarity of the genetic programmes underlying these patterns, a historical contingency (Newman 1988).

6. Conclusions

Is the human hand an adaptation or an exaptation? The variation of some features of the human hand possesses functional significance. These features could be uncontroversially classified as adaptations to specific roles if the term is used to describe form–function relationships. If the term makes reference to mechanisms, two viewpoints that represent two different conceptions of development and evolution (Linde-Medina 2010a) – in turn rooted in two different conceptions of organic matter (Linde-Medina 2010b) – should be distinguished.

From the externalist framework, when development is conceived as the implementation of a genetic programme, the existence of organizing principles of form generation – the law-like component of form – is ruled out. Form is arbitrary (subject to functional adequacy) and the cause of the existence of a feature is its functional significance. If a feature exists, it is because it has been forged by natural selection to meet external functional demands. When the only organizing principle of

biological form is natural selection, the only possibility available to explain form is in functional terms (i.e. the functional significance of these features is supposed to be the cause of their existence). From the internalist framework, the functional significance of these features could be the cause of their prevalence, but when development is conceived as a self-organizational, dynamical process, the cause of their existence would reside in how they are generated (i.e. in the internal principles of form generation).

I will make this point clearer by an example. A long and robust thumb is suited to perform large gripping forces and thus it could be useful for tool making and tool use. Its functional significance could be the cause of its prevalence. Under the assumption that there is a genetic programme for thumb identity, forged by natural selection to produce a specialized digit suited to some external functional demands, the thumb’s functional significance would thus be both the cause of its prevalence and its existence.

But if one considers that morphogenesis is carried out not by gene products alone but by the physical processes they differentially mobilize in multicellular aggregates (Newman and Bhat 2008), it is not possible to explain the existence of the thumb outside the context of its generative mechanism (the mechanisms of cartilage morphogenesis and differentiation, under particular local tissue conditions). The cause of its

form is in the way it is generated, apart from its functional role. The functional significance now would be just the cause of its prevalence. Note that any structure generated by the developmental mechanism will possess inherent functional properties independently of the subsequent use by the organism (i.e. from the external functional demands).

Current definitions of adaptation are bound to the externalist framework and, thus, to the idea that natural selection is a moulding factor. The results of selection are manifested in a moulding factor. The results of selection are manifested in a presumed genetic programme for development. The metaphor of the genetic programme, which during the early phase of molecular developmental biology was a possibility that had to be tested, seems to be untenable in light of recent advances in the study of development. A more suitable definition of adaptation, informed by the internalist framework, would refer to form–function relationships and incorporate the law-like component of form generation. A tentative definition would be as follows: a feature of a structure is an adaptation if it possesses functional significance useful to perform some biological role in the life of an organism and its variations have different prevalences due directly or indirectly to natural selection. Note that this definition does not purport to account the general form of the structure or its variations by natural selection, which would be explained by the internal organizing principles of form generation.

Remarkable features of the human hand, such as its pentadactyl pattern, remain unexplained by the externalist framework. These features are classified as exaptations. Note that the exaptation term is an explanatorily vacuous one: structures that cannot be explained in functional terms are called exaptations, but the term does not provide an alternative explanation. The study of these features can only be approached from the internalist framework.

It could be argued that some of the features studied by the internalist framework, like the quasi-periodic arrangement of skeletal elements, are not relevant for evolution, and so they remain unchanged across taxa and evolutionary studies deal with diversity. But this is a misleading interpretation. The dynamical laws are the cause of both the unity and the diversity of tetrapod limbs (Goodwin 1984; Zhu et al. 2010). Gene products can alter the parameters (e.g. diffusion rates of morphogens), initial and/or boundary conditions (e.g. limb shape and size) of the cartilage patterning process and thus lead to different skeletons, but these products have no meaning outside the context of the dynamical laws of limb patterning. Different species can differ in the spatiotemporal expression of some developmental genes, but making reference to these molecular differences without knowing their role in the context of the dynamical process of limb patterning is as inadequate as trying to explain the skeletal pattern just knowing the parameters values but removing the regulatory networks that these parameters tune. Different limb patterns can be correlated

with different developmental gene expressions, but a correlation is not a cause (explanation). In a scientifically sufficient account, the cause of a form (e.g. the human hand) resides in the dynamical laws by which it is generated (Goodwin 1984; Zhu et al. 2010) and its functional and adaptive roles are variations on the resulting themes.

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