Anatomical study: Descriptions of potential anthro anatomy

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We have a few broad ideas for implementing transformations. But first, it's important to describe what the *objectives* of those transformations are. Here, we'll take a few of these transformation objectives, analyze their implications in anatomy and physiology, and distill specific changes in morphology into separable research questions.

Specifically, we propose anatomical features for a variety of anthropomorphic ("anthro") figures and compare them to a human. Quadrupedal figures will use similar techniques with more extensive modifications. <u>These frameworks will help guide our research efforts, but are not set in stone. They are also not intended to be comprehensive or infallible</u>.

At the end of each anatomical discussion, we mention areas of research that are relevant for the body parts in question. Areas of research that are especially important or likely to give tangible results more quickly are marked with a "♦". Ultimately, deliverables will probably result from several combined approaches – no strategy is mutually exclusive with any other. Finally, we also list some established fields of science and medicine, whose experts we will meet with in more detail to optimize our research directions. We need to more fully understand all relevant, existing knowledge, even if the technologies we develop differ substantially from established practice.

Note that human anatomy figures were adapted from the Human Anatomy Atlas (VisibleBody, 2015). For clarity, anatomy models were traced to emphasize major features, and some structures and labels have been omitted or simplified if not essential to the argument.

<u>Head morphology</u>

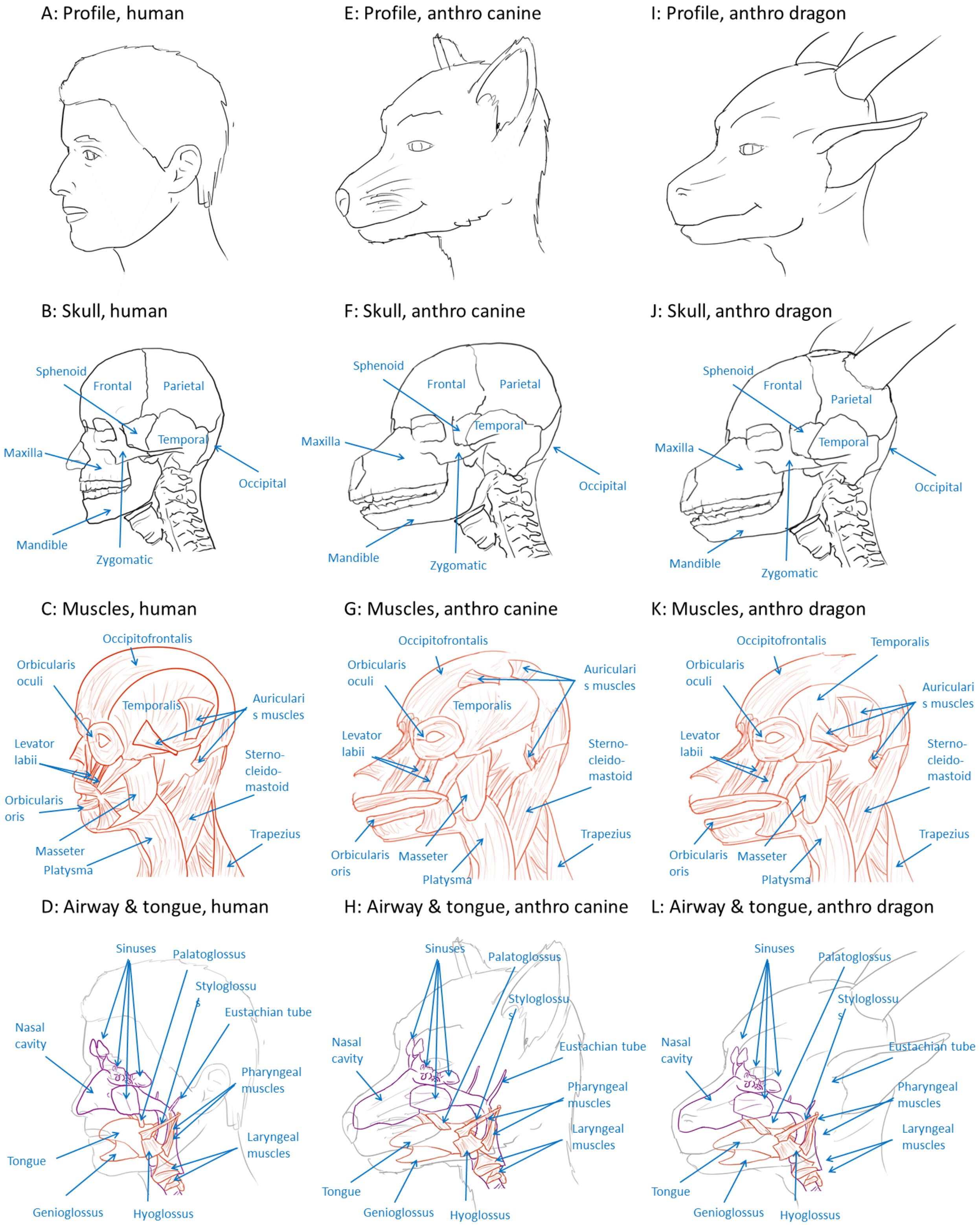
The head contains a sophisticated arrangement of sensory organs and muscles, and it is home to the most complex computational machine in the known universe. Meanwhile, the face is a memorable feature for others during social interactions, and an important window for one's inner emotions. Finally, verbalization requires precise coordination of the lips, tongue, larynx, and other structures, all with specifically evolved anatomies.

All these considerations make the head the most challenging target anatomy of our research. Therefore, we'll discuss features of human head anatomy (Fig. 1A-D) and propose anatomies for an anthro canine (Fig. 1E-H) and an anthro dragon (Fig. 1I-L), preserving expected functions as much as possible.

At a glance

- Muzzles will require lengthening of, or substitution of, the mandible and maxilla.
- Additional smaller cranial shape changes will include the orbits, sphenoid bone, zygomatic process, and temporal bone.
- In species with elevated ears, they may need (a) longer ear canals, (b) dorso-laterally displaced vestibulocochlear organs, or (c) a short closed-loop auditory signal repeater to maintain sound detection by the inner ears.
- We expect speech will not be negatively impacted, other than modest changes in voice tone due to larger nasal sinuses. Modified lips and tongues will function normally since we preserve the unique musculature controlling their complex humanoid movement.

Figure 1 – Head anatomies



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Descriptions of potential anthro anatomy

Skull

In terms of skull anatomy for both canid and dragon anthros, most of the adjustments will occur to the maxilla and the mandible (Fig. 1B, F, J). Additionally, to accommodate a dorsal-lateral-anterior movement of the eyes, and accentuation of cheeks, the orbits and zygomatic areas will be modified. These will also affect some portions of the frontal, in addition to the maxilla proximal to the orbits, and some limited portions of the sphenoid. Note that in all cases, internal braincase size can be maintained (internal view showing skull thickness not shown).

Projections from the face, such as ears and horns, will differ from anthro species to species. These projections will require some further modifications to the cranial skeleton. Anthro canines will ideally have ears placed higher on the skull (Fig. 1A, E). Alignment of external ears with ear canals and the vestibulocochlear system may require dorsal movement of portions of the temporal and zygomatic (Fig. 1F). In comparison, anthro dragons generally have lateral ear placement similar to humans (Fig. 1A, I), and won't require such alignments for the vestibulocochlear system. However, anthro dragons are often imagined to include horns – these might, for example, be mounted on the parietal (Fig. 1I, J).

Note that human anatomy has the skull's foramen magnum and the atlas (the first cervical vertebra) positioned immediately inferior to the braincase (not shown), whereas feral anatomy places those structures caudally (not shown). We don't plan to reposition these features for anthropomorphic anatomy. However, repositioning *would* be necessary for quadrupedal anatomy, and might be achievable through gradual remodeling, allowing the nearby volume of nervous system tissue to reshape through cellular growth and turnover without interrupting connectivity.

Muscles

For the most part, changes in muscle anatomy will closely mirror skull changes (Fig. 1B, C, F, G, J, K), with a few important notes to mention. For one, the auricularis muscles will be moved dorsally in canines to accommodate higher ear placement (Fig. 1E, G).

Another point of interest may be levator muscles around the lips. In humans, lips are moved in part through levator muscles anchored around the nose and eye orbits (Fig. 1C). Biomechanically, this may, or may not, be appropriate in anthros (Fig. 1G, K), since muscles anchored in the same way might instead pull the upper lip posteriorly, rather than in a purely dorsal direction. Therefore, it may instead be favorable to move the anchors for anthro lip levator muscles anteriorly, towards the snout (not shown), but this would require some consultations before deciding on this area's final anatomy.

Vocalization, airway, and tongue

We maintain the size and placement of vocalization and ingestion structures as much as possible (Fig. 1D, H, L). The lips and tongue are larger and displaced anterogradely. In support of a larger tongue, we specify larger surrounding muscles, e.g. enlarging the palatoglossus, genioglossus, and hypoglossus.

A change in the size of lips and teeth should only have modest effect on "b", "p", "f", "oh", and "oo" sounds while changes in the tongue should have modest effects even on "ee" and "aa" sounds (Niebergall et al., 2013). The voice box is unchanged (Fig. 1D, H, L), and neuroplasticity will assist in mental adaptation to different sizes and shapes of facial structures (Pourmomeny and Asadi, 2014).

Tone may change if the sinuses and nasal cavity are enlarged, since they resonate during vocalization. The thresholds between the mouth and pharynx, larynx, sinuses and nasal cavity also affect this (Lohmander et al., 2002; Stevens, 2000). It is common to notice tonal and 'roughness' differences, and/or 'nasality' changes in the voice when an individual has nasal congestion, an inflamed throat area, inflamed tonsils, or tonsillectomy. This appears to be a function of the ability to control the difference in air pressure ratio between mouth and nose (Andreassen et al., 1991). Since people with a tonsillectomy, or even complete nasal blockage, can still talk, a longer muzzle seems like a relatively minimal change, and should preserve speech!

Even so, some modes of failure in the shape of the skull and mouth affecting speech and breathing are known, such as cleft palates and velopharyngeal dysfunctions (Nachmani et al., 2013, 2017) (which can often be a result of insufficient growth and development of facial features and cranial/pharyngeal components (Xu et al., 2014)) and obstructive sleep apnea (Finkelstein et al., 2014). We need to be mindful of these in any designs for modifications to these areas. Mathematical models and equations are available which can help us further understand and predict impacts of facial remodeling on vocalization (Milenkovic et al., 2010).

Also note that as a secondary consequence of ear movement for anthro canines, (1) their vestibulocochlear organs may be moved laterally and dorsally, requiring longer eustachian tubes, or (2) their ear canals may be lengthened (Fig. 1H and not shown).

Research questions

- How can we reshape or replace the cranial bones, especially the maxilla and mandible?
- For species with elevated ears, (a) given longer ear canals, (a1) will auditory quality be preserved, and (a2) how should the ear canals be implemented; or (b) given displaced vestibulocochlear organs, how can we (b1) accomplish this movement of a delicate structure within larger cranial bones, and (b2) lengthen the Eustachian tubes to remain connected?
- How can we increase the size of certain muscles, such as the tongue and lip muscles, to remain proportional to the muzzle, and ensure they are functional in speech and other processes?
- What is the safest method to lengthen cranial nerves, including the optic nerves, to accommodate changed facial proportions?

Approaches

♦remodeling; ♦genetic mods; stem cells and bioprinting; neuroprosthetics; surgery; idle prosthetics/scaffolds

Expertise and consultation

♦ENT (otolaryngology); ♦plastic surgery; phonetics; orthopedics; neurology; osteology; muscle biology; biomechanics; prosthetics; opthalmologists

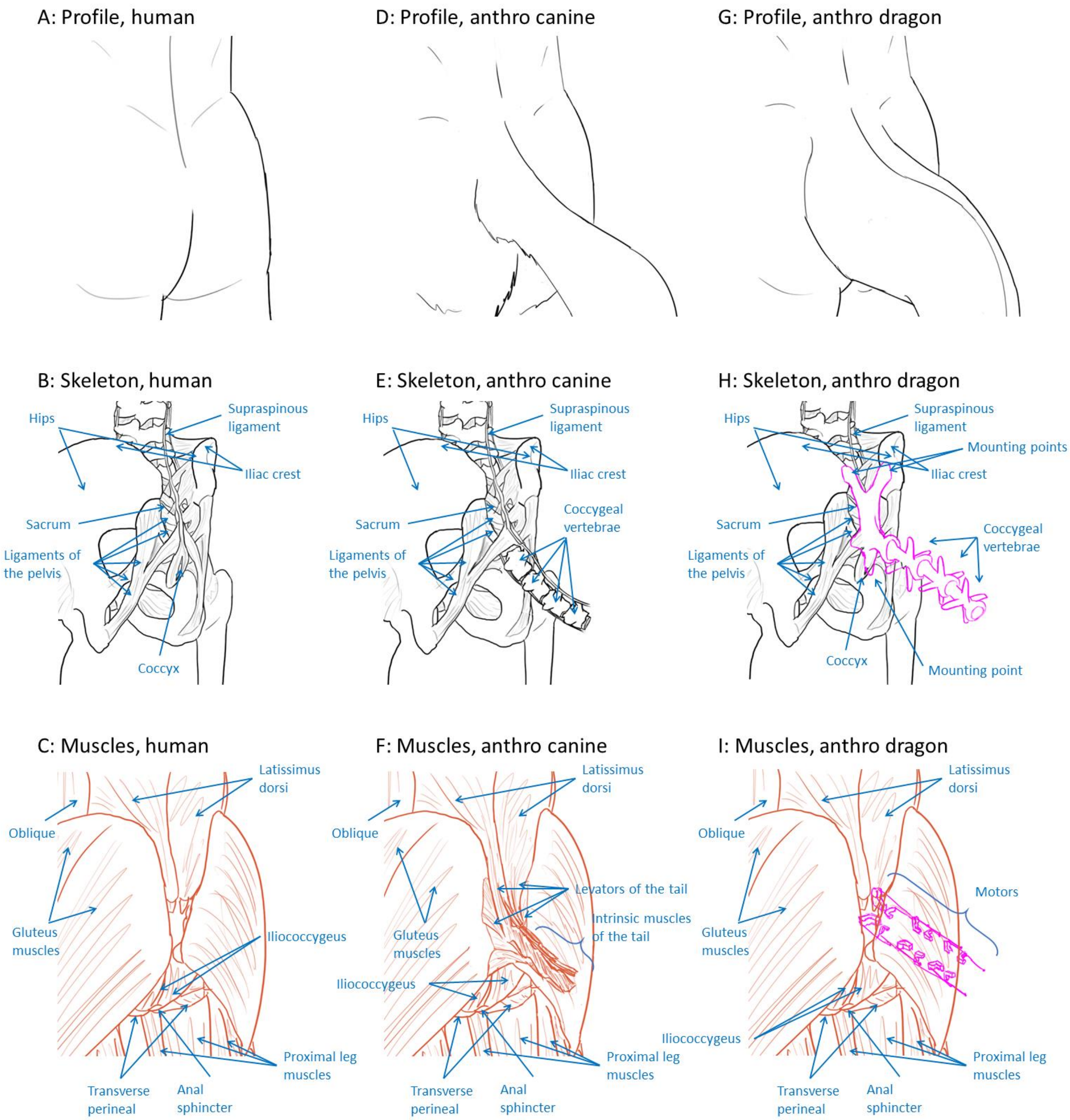
Tail morphology

The pelvic girdle and surrounding areas are complex anatomical structures frequently under heavy, dynamic strains and loads. An anthro's tail needs to work within this environment, while minimizing interference with the well-evolved anatomy that humans have evolved for bipedal locomotion. We've come up with two examples of how functional and aesthetically pleasing tails can be added to a human's pelvic area, while staying within these constraints (Fig. 2). Sticking to our canine and dragon anthro examples, we'll propose neuroprosthetic and biological solutions.

At a glance

- Tails will require a long, prehensile mass integrated at or near the base of the spine, the coccyx.
- Additional skeletal changes may include the sacrum and the dorso-medial area of the hips.
- The ligaments in this area are complex. This complexity can be ignored if we go with neuroprosthetics, but will be challenging if we attempt to fully integrate a biological tail.
- Some conscious motor control of the tail should be facile. Sensory innervation should also be possible through using existing nearby nerves in the dermatome.

Figure 2 – Tail anatomies



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Skeleton

Humans' vertebral columns terminate in the sacrum and coccyx – two bony formations that each develop from several sacral and coccygeal vertebrae, respectively. These are augmented with a network of thick ligaments, including the ligaments of the pelvis, that connect hips, the sacrum, the coccyx, and other vertebrae. Some ligaments terminate on the coccyx, including the supraspinous ligament (Fig. 2B).

As one example to how these can work in an anthro, we have drawn a canine anthro with a biological tail (Fig. 2D). The sacrum and ligaments of the pelvis are largely retained. However, the coccyx is replaced with individual coccygeal vertebrae. Ligaments that normally terminate on the coccyx, including some ligaments of the pelvis, as well as the supraspinous ligament, will be lengthened and adjusted as necessary. It's also important to consider that the creation of new tail muscles will need new insertion sites on the hips and vertebrae.

As a second example, we illustrate how a neuroprosthetic tail might work in this context (Fig. 2G). Human structures are retained, though with some slight reshaping as needed. In particular, the coccyx is not modified, to minimize biomechanical changes (Fig. 2H). Instead, the neuroprosthetic is affixed at a few locations that are immobile and superficial. The left and right medial iliac crest, the dorsal face of the coccyx, and a few locations on the sacrum may be good foundations for the tail.

Muscles

In humans, the coccyx, sacrum, and surroundings are key termination points for muscles throughout the torso, abdomen, and legs. The superficial muscles are shown (Fig. 2C), though deeper muscles including the intrinsic muscles of the spine are also crucial (not shown). But, since there are no muscles that immediately overlie the sacrum or coccyx, carefully engineered modifications will be tractable.

Tails in other animals are controlled at the base by levator muscles, and along their length by a variety of extrinsic and intrinsic muscles (Shinohara, 1999). These can be recapitulated in an anthro with a biological tail (Fig. 2F), though again some care will be needed for proper insertion of these new muscles on the hips and vertebrae of humans. On the other hand, in the case of a neuroprosthetic tail, movement can be driven by self-contained motors and other mechanisms (Fig. 2I).

Research questions

- How can we best structurally integrate the tail with the body? (a) If biological, how will we reconfigure the sacrum, coccyx, and nearby ligaments? (b) If neuroprosthetic, then (b1) how will we stably integrate it with bone, and (b2) will the neuroprosthetic be sub-dermal, or will it instead provide a full synthetic skin requiring integration with surrounding skin?
- How can we power tail movement adequately and precisely?
- How can we best connect the tail for conscious motor control and for sensory innervation?

Approaches

♦neuroprosthetics; ♦stem cells and bioprinting; genetic mods; surgery; remodeling

Expertise and consultation

♦orthopedics; ♦prosthetics; neurology; osteology; muscle biology; ligament biology; kinesiology; biomechanics

Forelimbs

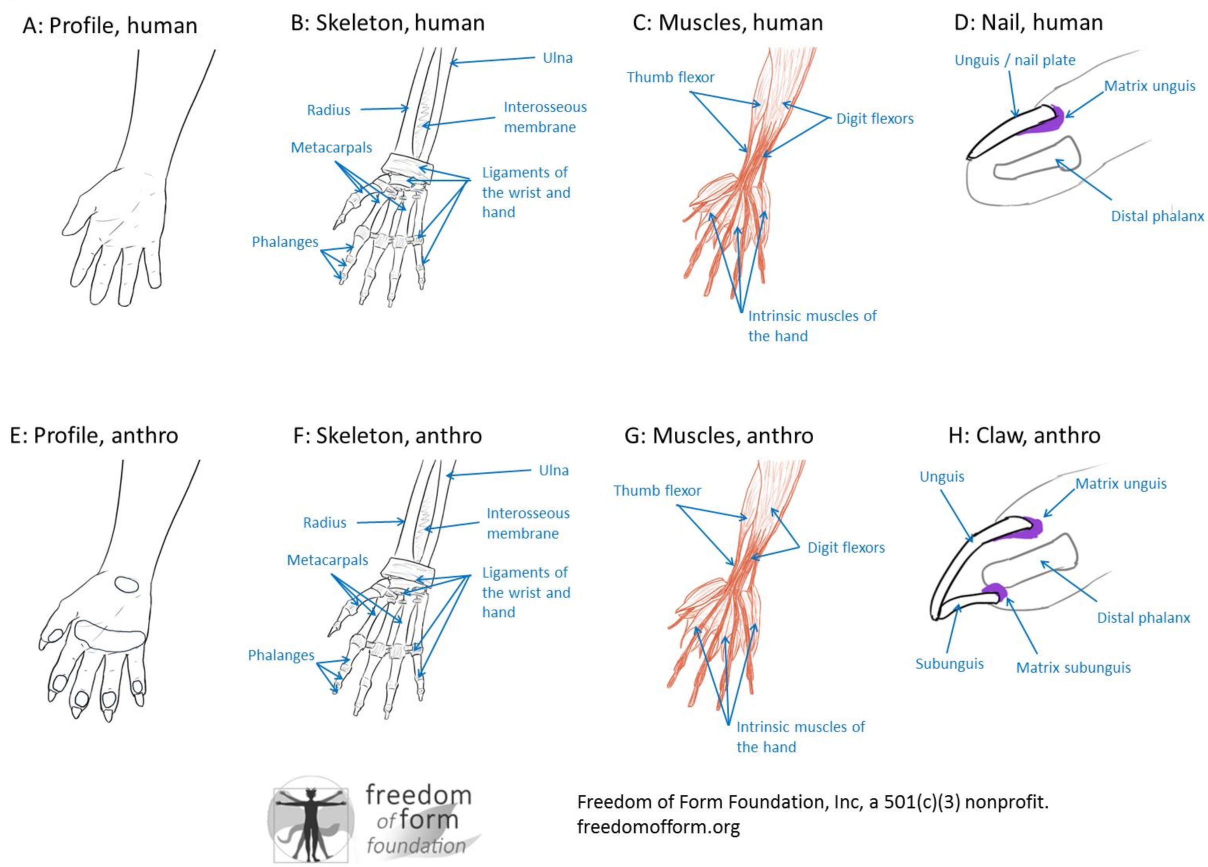
Human forelimbs are highly dexterous, due to individual control of fingers and an opposable thumb, and even the ability to rotate (supinate and pronate), deviate, flex, and extend the wrist relative to the elbow. Forelimbs are rooted at the shoulder, and the musculature that controls their movement extends as far away from the hands as the chest and the back.

Most anthros won't need large forelimb modifications, assuming they keep the same number of digits. The aesthetic of forepaws can be accomplished mainly through slight lengthening and widening of the wrist and metacarpals, 'fattening' the soft tissue of the digits, and the exchange of nails for claws.

At a glance

- The most visible modifications to the forelimbs are expected to be minimal in terms of skeleton and muscle impact. Common changes might include claws, pawpads, and 'fattening' the distal soft tissue of digits.
- Additionally, some changes might include lengthening and widening the wrist and metacarpals, and reduction of the number of digits from 5 to 4.

Figure 3 – Forelimb anatomies



Skeleton

The human wrist can rotate in many different axes due to the wrist joint itself, as well as the separation between the forearm bones (the radius and ulna). Here, wrist supination and pronation involve the radius and ulna crossing over one another (Fig. 3B). These should be retained in an anthro (Fig. 3F).

The major bones of the hand and digits are the metacarpals and phalanges. For anthro forepaws, it's possible that only the metacarpals would need lengthening and widening. An additional modification might involve thickening and strengthening the distal-most phalanx to structurally support claws (Fig. 3F, H).

Muscles

The dexterity of wrist and digit movements requires complex musculature. Most of these muscles originate near the elbow (from the humerus, radius, or ulna), though a few muscles involved in fine finger movement are intrinsic to the hand. We show a few of these muscles (Fig. 3C), but have hidden others for clarity in this brief overview. Assuming an anthro maintains the same number of digits, no changes to musculature should be needed (Fig. 3G). However, if a reduction in the number of fingers is desired, it might be reasonable to merge or remove musculature for the ring finger – this finger's musculature is simpler than the others, and is also shared with the pinky and middle fingers (not shown).

Nails or claws

Nails are keratinous structures that are produced from a population of actively dividing cells at the matrix unguis (Fig. 3D). New keratinous material causes the nail plate (the unguis) to push forwards. Claws are very similar – actually, nails are just simplified claws, evolved in primates. Besides the unguis, claws also have a slower-growing subunguis (Fig. 3H). Differential growth causes claws to develop their stereotypical curved shape.

Pawpads

Pawpads protect animals' paws from rough surfaces, sharp objects and other potential dangers. These specialized surfaces are present most often at the palm and at the ventral, distal surface on each phalange. They are principally made of thick, durable skin, with a high concentration of melanin, and are layered over subcutaneous collagenous (for flexibility) and adipose tissue (for padding). Pawpads are generally hairless, but exceptions include arctic foxes and red pandas, whose pawpads extrude fur for additional protection from extreme temperatures and wear.

These might be desirable traits to recapitulate in an anthro – pawpads aren't just aesthetic. At the same time, anthro pawpads still require flexibility, so our designed tissues may compromise between the thickness of pawpads and normal human skin. Additionally, the pawpads will need to be sized, shaped and positioned such as will not hinder dexterity of either the palm or the digits.

Research questions

- How can we modify or replace nails with claws?
- How can we add pawpads, or modify existing skin to produce pawpads?
- How can we safely modify wrist and metacarpal size?
- How can we safely change the number of digits as desired?

Approaches

♦stem cells and bioprinting; ♦genetic mods; ♦remodeling; idle prosthetics/scaffolds; surgery

Expertise and consultation

♦orthopedics; ♦plastic surgery; osteology; muscle biology; ligament biology; prosthetics

Hindlimbs

Fursonas most often include changes to hindlimbs, involving claws, possible changes to the number of digits, and sometimes a transition from plantigrade to digitigrade locomotion. Therefore, hindlimbs are an important anatomical target of freedom of form. We've drawn up an example of how digitigrade feet might differ from plantigrade feet, in order to help frame specific research questions.

Hindlimbs are anatomically similar to forelimbs. However, they experience greater mechanical strain and load. The proportions of the upper legs, lower legs, feet and toes must be significantly different from human plantigrade proportions, to achieve efficient balance, locomotion and power transfer, and to be aesthetically correct.

At a glance

- Some visible modifications, i.e. claws, pawpads, and 'fattening' distal soft tissue, will be moderately easy (as in the forelimbs).
- If digitigrade posture is desired, metatarsal and phalanges will need significant lengthening and strengthening, and the lower and upper leg may need shortened proportionally. This must be accompanied with stronger ligaments and muscles, especially in the foot.
- Balance while standing bipedally, in a digitigrade posture, should be fine with a sufficiently large load-bearing base (e.g., larger ground-contact area of digits). Humans with bilateral leg prosthetics have great mobility (e.g. Hugh Herr) despite reduced muscle control of their feet and digits.

Skeleton

In the first example (Fig. 4E), reminiscent of canines, we specify a five-toe design that shortens toe 1 to reassign it as a dewclaw, and lengthens toes 2-5 significantly. In the majority of digitigrade species, dewclaws are diminutive forms of toe 1, and so this layout is an option we will consider with tried and tested morphological evolutions in mind. Toes 3 and 4 will be lengthened to stand forward of toes 2 and 5 in order to achieve a stable weight distribution and a familiar canid pawpad shape, with vulpines receiving longer toes 3 and 4 than canines or lupines.

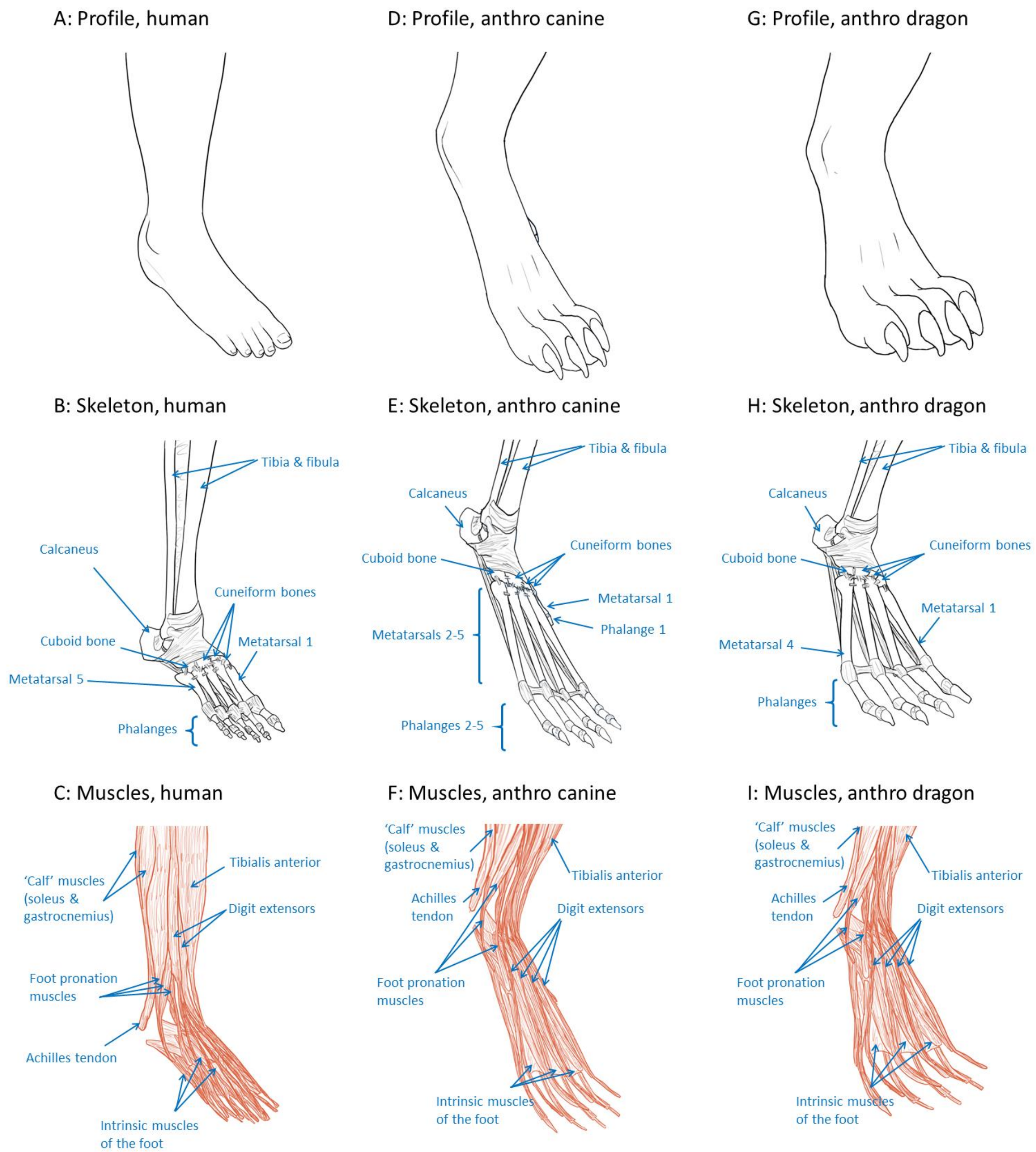
In the second example (Fig. 4H), we specify a four-toe design that keeps the human equivalent toes 1-4, and ablates toe 5. Note that since toe 5 receives muscles from the leg involved in foot control (rather than simply digit control), these muscles will instead need to insert onto toe 4. As well, the cuneiform bones will need slight adjustments to fit wider metatarsals 1-4.

In both examples, some variability on a case by case basis of the proportions and dimensions will be possible, to fit individual tastes.

Muscles

The load-bearing nature of the now-elevated ankle and digit joints requires strengthened and balance-adjustable musculature. Most of these muscles originate near the knee (from the thigh, tibia, or fibula), though a few muscles are present in the foot itself for intrinsic flexion and balance correction. We show a few of these muscles (Fig. 4C, F, I), but have hidden others for clarity in this brief overview. The major changes to musculature will be a shortening but also increase of width in the calf muscles, and a lengthening and thickening of intrinsic muscles and tendons in the foot (Fig. 4F, I). As discussed in the "Skeleton" section, some additional considerations of muscle anatomy will be needed for either reductions in the number of toes, or reconfiguration of the 'big' toe to the 'dew claw' position, if desired.

Figure 4 – Hindlimb anatomies



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Nails, claws, and pawpads

Hindlimb claws and pawpads will be very similar to those described for the forelimb above (Fig. 3D, H, I). However, we expect that hindpaw claws should be thicker and mechanically stronger, and have a slower growth-rate than forepaw claws (similar to how human toenails grow slower than fingernails). We would also expect hindpaw pawpads to be thicker and have a rougher texture.

Research questions

- Similar to the forelimbs, how can we modify or replace nails with claws?
- How can we add pawpads, or modify existing skin to produce pawpads?
- How can we safely modify ankle and metatarsal size, especially for digitigrade feet?
- How can we safely change the number of digits as desired?
- How can we adjust footpaw design for optimal balance?
- What skeleton and muscle designs will be of sufficient mechanical strength?

Approaches

♦stem cells and bioprinting; ♦remodeling; ♦genetic mods; idle prosthetics/scaffolds; surgery

Expertise and consultation

♦orthopedics/podiatry; ♦plastic surgery; ligament biology; osteology; muscle biology; prosthetics

Wings and flight

Flight has been tried and attempted in various ways by human beings over the millennia, and was finally made practical by the Wright Brothers' historic powered flights. Contemporary crafts like passenger airplanes make flight a bit…excruciating, leaving unassisted flight a bit of a dream. Among furries and scalies are those who wish to fly under the power of their own wings. This might seem far-off, but we did the math: it should be possible soon.

Here, we describe some of the basic anatomy required for an anthro capable of flight, whose wings constitute a third pair of limbs placed just caudal to their shoulders. We support flight's feasibility in metabolism and muscular force generation. We still have some concerns, such as optimizing bone structure or the selection of load-bearing materials to prevent fractures caused by flight muscles, though if necessary these could be solved through the implantation of reinforcing materials.

At a glance

- Flight should be possible. The math works out reasonably for metabolism and force generation. We do have some remaining concerns over bone strength that, if nothing else, can be solved with surgical reinforcement.
- We generally assume people wanting wings will want to retain their forelimbs and hindlimbs, meaning the wings will constitute a 3rd pair of limbs.
- We've designed a novel wing-shoulder anatomy, taking inspiration from birds and bats while respecting the current anatomical realities. It should allow a full wing-beat cycle in flight, and not impede forelimb function while on the ground.
- Either neuroprosthetics or biological tissues are expected to work well.

Metabolism

When animals fly, they use energy rapidly per unit of time, but the energy cost per distance travelled is actually *7.5-fold lower* than for land-based animals (Butler, 2016). Moreover, the larger a flying animal is, the more energetically efficient it is: hummingbirds weighing 3.5 g burn energy in excess of 200 Watts per kg of body mass in level flight, whereas bar-headed geese, weighing nearly 1000x that (2.8 kg) consume around 48-50 W/kg of body mass in level flight (Butler, 2016; Ward et al., 2002).

Animals that tend to soar or glide are even more efficient. Black-browed albatrosses (around 4 kg) metabolize around 8.8 W/kg when actively flying, or only 2.4 W/kg when gliding (Scanes, 2014).

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Griffon vultures (around 7.5 kg) metabolize around 4.4 W/kg during take-off, and 2.03 W/kg while gliding (Duriez et al., 2014).

A creature, whether person-sized, or larger, should be able to actively fly for around the same metabolic effort as running, without including any enhancements to athletic performance. They should be able to glide for very little effort.

An anthro with a tail, wings, and flight muscles might weigh 83 kg (185 pounds). Let's say they are a bit less efficient than an albatross, and draw around 12 W/kg to actively fly. For 15 minutes of active flight, this anthro would consume 12 W/kg * 83 kg * 0.25 hour = 249 Watt-hours, or 214 Calories. In comparison, healthy people can produce 11.73 W/kg when jogging at 2.75 m/s (6.2 mph). Also similar to the albatross, we can guess gliding costs 3 W/kg. This is slightly less effort than walking at 1.25 m/s (2.8 mph) (Farris and Sawicki, 2012). These metabolic estimates, even if wrong by more than a factor of two (i.e., on parity with strenuous activities like sprinting), won't affect the conclusion: human metabolism can power active flight, without any athletic enhancements.

Force generation

Birds fly using a combination of their wings and tail. Lift is mainly produced by the wings, while the tail might contribute up to one-third of the total (Thomas, 1997). For a bird to stay in level flight, their lift must counteract gravity: a duck weighing just under 1 kilogram (2.2 pounds) will experience gravity of 9.76 Newtons (2.2 pounds of force), so they must exert 9.76 N of lift to stay in the air, using some combination of their wings and tail. Additional force exertion would be needed to create any thrust.

The pectoralis muscles are the major flight muscles of birds. Located on the torso, they pull each wing downwards, exerting force against the air, downwards and backwards. This creates a mixture of lift and thrust. However, bird wings are like "bad" levers, where lift occurs far from the fulcrum (the shoulder), and the pectoralis muscles are much closer to the shoulder. As a consequence, in *Anas platyrhynchos* ducks, the pair of pectoralis muscles together exert 11-fold more force (107.5 N compared to 9.76 N) than would be needed to counteract gravity in level flight (Williamson et al., 2001). Even so, this amount of force is "comfortable" for birds, because the force exertion in level flight is around 30% of the maximum predicted exertion expected based on the muscle's size (Dial and Biewener, 1993).

These muscles together weigh 0.135 kg, or 13.6 % of the ducks' mass (Williamson et al., 2001). For comparison, pigeons have a pectoralis mass of about 18% of their body (Dial and Biewener, 1993), and cockatiels devote about 20% of their mass to the muscles (Hedrick et al., 2003). However, lower pectoralis : body mass ratios are possible. Some raptors have pectoralis muscles representing 12 to 14% of their body mass (McNab, 2012). Remarkably, a wanderer, a type of large albatross weighing around 9 kilograms, has pectoralis muscles that only take up 6% of its body mass (Lindsey, 2008).

We have estimated equivalent muscle mass and force exertion required for flight of an anthro. To show that these numbers are reasonable, we calculate them three different ways, and they all lead to the same result (Box 1): the pectoral muscles shouldn't need to be more than 17% of body mass, and could even be 12% of body mass or less while still easily supporting flight. Therefore, an anthro can have flight-capable muscles of reasonable size; there is no "scaling problem" that requires absurdly large muscles to generate the required forces.

Other flight metabolism and muscle force considerations

Even though those values are already reasonable, there are a few things we can do to make flight even easier for a person transformed for flight: (1) their heart may be strengthened to increase overall body power output; (2) their pectoralis muscle may be moved laterally, while the wing shoulder-joint may be moved proximally, improving the lever ratio (and reducing required force) of the pectoralis to the wing's lift; (3) increasing elasticity in the wing, making force-generation more even throughout the wingbeat, reducing peak force requirements; (4) pursuing weight-saving strategies like design of lightweight limbs or neuroprosthetics, and reducing the mass of some bones and muscles; (5) augmenting pectoralis force exertion with an elastic band or spring, whether a biological tendon, or a biocompatible material; and (6) allowing 'locking' of wings, like albatrosses can do to reduce force requirements (Lindsey, 2008).

It's also worth pointing out a couple things that will *not* greatly affect flight muscle needs: take-off, and forwards thrust. Both of these are approximately negligible in our estimates of flight muscles. Take-off and landing aren't much more stressful than the rest of flight – a lot of power is provided from the legs in pushing off from the ground or landing (Chin and Lentink, 2017; Provini et al., 2014). And, forwards thrust only needs to be sufficient to counteract drag. The lift-to-drag ratio is often around 11:1, 15:1, or 22:1 in birds (Doane, 2011; Parrott, 1970; Wikipedia, 2018a), meaning only 9% to 5% of the magnitude of lift force is needed for thrust while cruising.

Skeleton

The skeletons of birds and bats are well-adapted for flight. We can take some inspiration from their skeletons, without needing to copy all structures precisely. Bird and bat ribcages are strong, having thickened ribs and a modified sternum called the keel. Therefore, we've indicated thickened ribs in the most likely area of increased stress (Fig. 5E).

Another important structural feature of birds is the acrocoracohumeral ligament (Baier et al., 2007). This ligament is very small, but quite strong - able to withstand forces 39 times greater than the animal's body weight. Without this ligament, the shoulder immediately dislocates if flight is attempted (Baier et al., 2007). It will be important to include an equally strong ligament for flight of any anthro or quad (not illustrated in Fig. 5E).

Of course, final anatomical decisions, especially those which may impact: (1) specific mechanical function of the diaphragm, (2) flexibility (bending forwards and backwards; side-to-side; and rotation) of the torso and abdomen, and (3) mechanical strength of flight-related structures, will only be made after thorough consultation and testing.

Muscles

The most important muscles for flight are the pectoralis muscles, as described above in "Force generation". We have attempted to draw flight-capable pectoralis muscles to an approximate scale in our anthro flyer example, using a cross-sectional area of 663 cm^2 divided by 2 for the left wing (Fig. 5F, and Box 1 Method 2). Smaller muscles, due to lower force generation specifications, or due to more significant pennation of individual muscle fibers (reducing the anatomical cross-section while preserving the physiological cross-section), should still enable flight.

There are other muscles throughout the wing in both bats and birds, similar to the musculature of the human forelimb (Biewener, 2011; Than, 2007; Tian et al., 2006). These are used to shape the wing throughout the wingbeat, but undergo relatively small strains.

Birds have an additional flight muscle called the supracoracoideus (Biewener, 2011). This muscle pulls on the wing humerus during upstroke. However, this muscle is very small in albatrosses (Brooke, 2018), so the supracoracoideus may not be as necessary for larger fliers or those that tend to glide more frequently. Furthermore, bats (like any mammal) completely lack a supracoracoideus, instead using their deltoids for wing upstroke. Therefore, we've drawn a traditional deltoid for our anthro flyer (Fig. 5F).

Box 1: Pectoralis muscle calculations

Assumptions: We're specifying an example anthro of 5 feet, 9 inches tall, at an ideal BMI of 21, for a body weight of 140 pounds. We'll allow an additional 30% of body weight (42 pounds) for a tail, wings, and any other modifications, totaling 182 pounds. Going into metric, this is 83 kg. This anthro will experience 814 Newtons of downward force due to gravity. Therefore, in level flight, they must exert 814 Newtons of force from their flying surfaces, including their wings.

Values of maximal muscle force in humans include 32.1 N/cm^2 (de Monsabert et al., 2017), 27 N/cm^2 (Barker et al., 2014), 46 N/cm^2 (Häkkinen and Häkkinen, 1991), and over 54 N/cm^2 (O'Brien et al., 2010), for a variety of muscle types. Actual forces will depend on the relative angle of muscle fibers to the overall muscle (the pinnation angle), and the composition of the fibers. Nevertheless, let us say conservatively that pectoralis muscles will work at a maximal 27 N/cm^2 of anatomical cross-section area.

Method 1 (Calculated from lift requirements): We'll assume wings are providing 80% of the lift for an anthro, or 651 Newtons (tails can generate perhaps one-third of lift (Thomas, 1997; Usherwood et al., 2005), but we'll say only 20% of lift is provided by tails to be conservative).

The average center of lift in each wing is very far from the wing-shoulder, putting the pectoralis muscle at a mechanical disadvantage where it connects with the humerus – acting like a bad lever. This mechanical disadvantage is about 11:1 in pigeons (Baier et al., 2007). Assuming this ratio scales with body size, and the wings are producing 651 Newtons of lift (plus a small amount of thrust), then both pectoralis muscles will need to produce 7,161 N on average during level flight.

However, pectoralis contraction might be limited to, say, 67% of the overall wingbeat (Hedrick et al., 2003). So, the actual peak pectoralis force will need to be proportionally greater than the average; therefore, both pectoralis muscles will need to produce around 10,688 N when they are contracting maximally. If we say that this further represents 60% of isometric force, then we come to a pectoralis force specification of 17,813 N.

Therefore, considering 27 N/cm^2, a flying anthro will require 660 cm^2 of bilateral pectoralis cross-section area. We'll also say the muscles should be 20 cm long. Simplistically, muscle volume will be 13,195 cm^3. At 1.06 g / cm^3, the muscles will weigh 14.0 kg, or 16.9% of body mass.

Method 2 (Scaling up of bird forces): Ducks (0.995 kg) output a combined 107.5 Newtons from their pectoralis muscles during level flight (Williamson et al., 2001). Gravity would exert 9.76 Newtons on these ducks, meaning that measured pectoralis output was 11 times the force of lift.

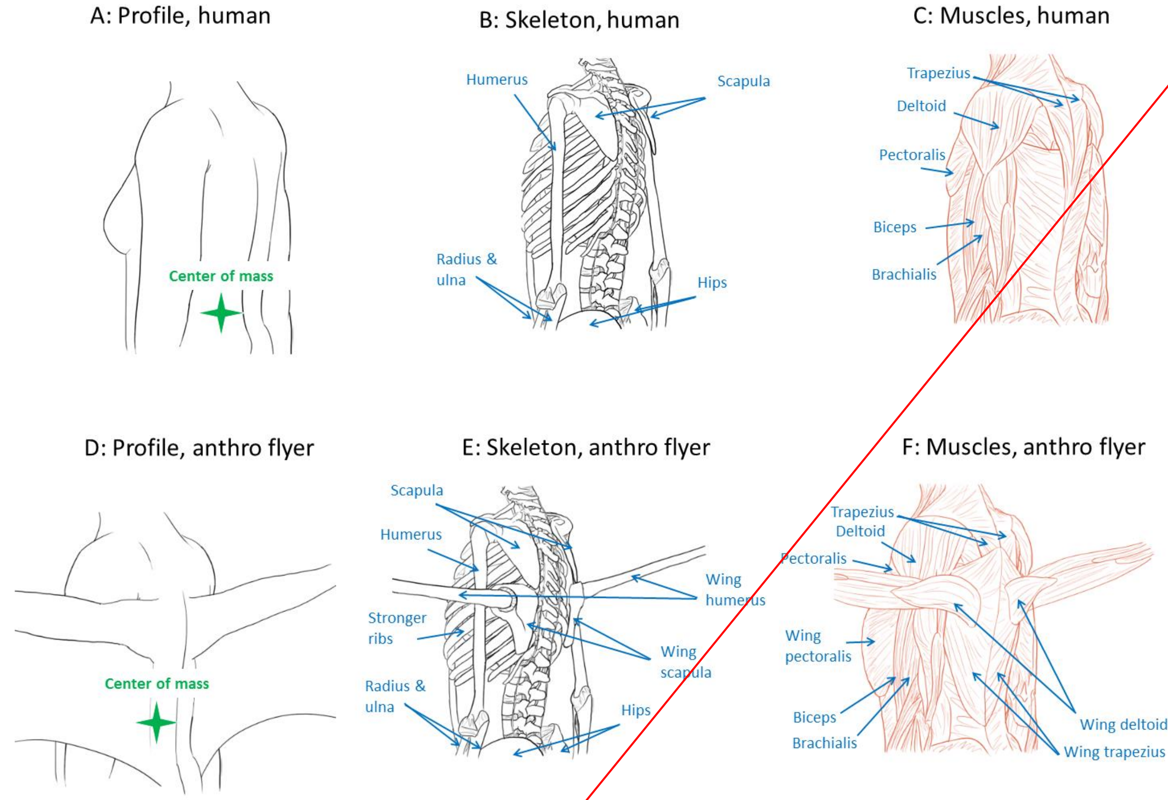
An anthro weighing 83 kg will experience 814 Newtons. Keeping the ratio of pectoralis force : gravity force constant, pectoralis muscles must exert 8956 N to maintain level flight. We'll say anthro pectoralis muscles are working at 50% capacity (Biewener, 2011), and are able to exert 17,912 N of force.

Therefore, considering 27 N/cm^2, a flying anthro will require 663 cm^2 of bilateral pectoralis cross-section area. We'll also say the muscles should be 20 cm long. Simplistically, muscle volume will be a bit less than 13,260 cm^3. At 1.06 g / cm^3, the muscles will weigh 14.1 kg, or 17% of body mass.

Method 3 (Direct scaling of large muscle masses): Some raptors have pectoralis muscles representing 12 to 14% of their body mass (McNab, 2012). Therefore, if we assume muscle mass in an anthro is simply 12%, we can estimate the weight support it can provide in flight.

12% of body mass would be 9.96 kg. A similarly-sized muscle in horses is the gluteus medius, weighing 10 kg in the Quarter Horse (Crook et al., 2008). This muscle is 57 cm long and can produce 13,152 N of isometric force. Since this would be a bit too long of a muscle, we can scale the muscle to be 29 cm long, doubling its cross-section area, and therefore doubling its maximal force generation to 26,304 N. If this is operating at an 11:1 disadvantage, this would support up to 2,391 N of lift. This lift, plus an additional 20% of body weight support from the tail, could provide 2554 N of lift, or up to 314% of the lift necessary for an 83 kg animal.

Figure 5 – Flight



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Research questions

- How will we strengthen the nearby anatomy, such as ribs, against the forces generated in flight?
- What specific parameters are needed? Wing span, wing loading, pectoralis strength, etc?
- How flexible should the wings be? Moderately rigid, like birds, or more flexible, as in bats?
- How can we power wing movement adequately and precisely?
- How can we best connect the wings for conscious motor control and for sensory innervation?
- What measures can we take to make metabolism for flight, e.g. heart and lung capacity, easier and more comfortable?

Approaches

♦neuroprosthetics; ♦stem cells and bioprinting; ♦genetic mods; surgery

Expertise and consultation

♦prosthetics; ♦orthopedics; ♦neurology; muscle biology; osteology; ligament biology; biomechanics; ornithology and chiropterology; cardiology; pulmonology

Superseded. Check freedomofform.org for updated information.

Skin, fur, and scales

Skin is the largest organ of the body. It is the barrier between the exterior and interior, the division between the hostile world of bacteria, dust, foreign objects and potentially dangerous substances, and the protected and controlled environment of our vast numbers of cells. Our most exposed part of the epithelial layers of the body, skin must at once protect from thermal extremes, retain and deflect water (but also release sweat), and if damaged, it must be able to repair itself. Transformed individuals may want skin coated in thick fur, feathers or scales, with potential benefits to insulation, flight capability enhancement, and armor. Color patterns can be displayed in skin, fur, feathers, and scales, allowing a form of self-expressive creativity for the transformed individual.

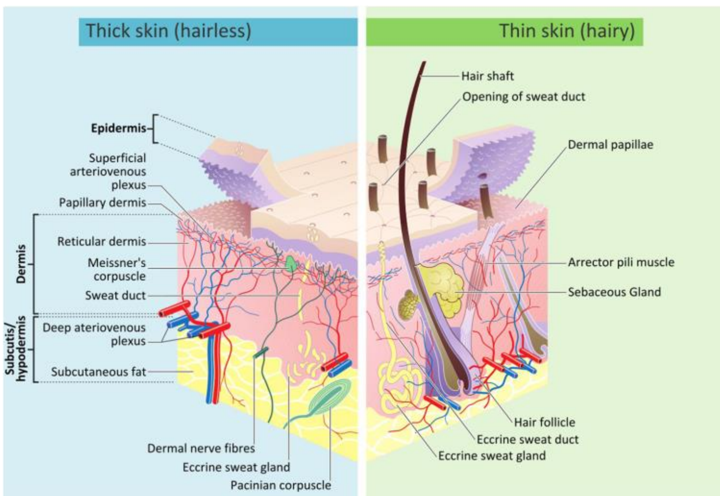
At a glance

- Human skin already has many of the necessary cell types and pores to grow fur, feathers or scales.
- Patterns and pigmentation are controlled by processes initiated during embryonic development. It might be possible to mimic these processes, or to create artificial methods to 'draw' fur, scale or feather patterns and colors onto the body.
- Whether scales, feathers or hairs/fur grow, is a matter of which types of keratin structures are produced in what relative quantities.
- Genetic editing, pharmacological or surgical options may be possible.

Skin

The outer protective layer of the body, skin has layers common to all mammals, reptiles and birds: the epidermis, the dermis, and subcutaneous fat and tissues. Types of skin differ via modifications in this pattern (Fig. 6). The epidermis contains a large population of keratinocytes, durable cells that help deal with day-to-day abrasions and impacts. These cells are replaced regularly, progressively displacing old ones upwards until they are lost or shed.

Figure 6 – Skin, fur, and scales



(Wikipedia, 2012) under license: CC BY-SA 3.0

The dermis is supplied by capillaries, and is also extensively innervated by sensory structures that detect touch, pressure, vibration, temperature, etc. These sensory structures include Meissner's corpuscles, Pacinian corpuscles, Merkel cells, Ruffini corpuscles, and free nerve endings (Fig. 6 and not shown). Additionally, the dermis contains sweat glands, in animals that can actively cool themselves through sweating.

Hair, fur, feathers, and scales

Fur coats often consist of a combination of different hair types: (a) an inner-most downy insulating layer of fine, curvy hairs, (b) an intermediate layer, and (c) a layer of stronger, straighter 'guard' hairs that help with waterproofing and physical protection. All these hairs are rooted in the dermis, and contain individual erectile muscles, the arrector pili, between the dermal root of each hair and the epidermis. Each hair also has a sebaceous gland to keep it oiled.

Feathers and scales share evolutionary origins with hair (Di-Poï and Milinkovitch, 2016). Scales evolved first, whereas feathers may have developed in dinosaurs for improved insulation, evolving more colorful patterns from sexual selection, and improving aerodynamic ability for gliding, e.g. for jumping gaps or pouncing prey.

Patterning and pigmentation

Skin pigmentation is provided by melanins, which naturally consist of brown, black, and red subtypes. Melanins are produced by melanocytes before being taken up by keratinocytes (Wikipedia, 2018b). Furthermore, the pigmentation of hairs and fur is accomplished by the transfer of melanin pigment from melanocytes and other cells that surround hair follicles into the keratinized hair shafts (Slominski et al., 2005). Similarly, melanin is a major source of plumage coloration of birds (Galván and Solano, 2016). Other compounds are used in animals as well, such as carotenoids and psittacofulvins (Wikipedia, 2017, 2018c). Nature further expands its color palette through vibrant, iridescent nanostructures that manipulate light at specific wavelengths, such as in peacocks (Galván and Solano, 2016; Wikipedia, 2018d).

Pigmentation is assembled into larger patterns, like spots, stripes, and splotches through a variety of mechanisms in nature. The mechanisms are incompletely understood, but clearly have both epigenetic and heritable components. Female calico cats are a famous example – their splotches are formed from the random inactivation of an X chromosome in very early embryogenesis (e.g. two- or four-cell stages). Meanwhile, ordered stripes and spots appear to form in mid-to-late-development in fish, and involve movement and self-sorting of cells using molecular cues (Singh and Nüsslein-Volhard, 2015). Sequential repetition of this process results in multiple stripes (Singh and Nüsslein-Volhard, 2015). Molecular and cellular interactions are under additional control and feedback resulting in complex interference patterns (Grandin and Deesing, 2014). It's worth noting that some natural patterning mechanisms appear to correlate with behavioral and neural development (perhaps owing to neural crest cell origins of melanocytes) (Grandin and Deesing, 2014), so any pigmentation and patterning systems we engineer will need to avoid cross-talk with neural mechanisms.

Between natural and synthetic or bioengineered pigments, it will be tractable to provide a vivid palette to suit one's desires for skin, fur, scales, or fur coloration. Iridescent nanostructuring may be more difficult to bioengineer, but should likewise be possible to provide eventually. The higher-order patterning of pigmented skin, feathers, scales or fur will be possible to create or adjust by either mechanically arranging pre-differentiated follicles or by distributing similar patterns of hormonal signals to those present in fetal development.

Descriptions of potential anthro anatomy

Research questions

- If we use a neuroprosthetic containing synthetic skin, it will need to blend smoothly into nearby biological skin. What sorts of micro-structure and chemistry will be needed to guarantee a strong, sterile, and seamless transition between natural and synthetic skin?
- Thermal considerations: how can we ensure someone with fur or feathers won't overheat? Will sweat glands be appropriate, and sufficient?
- How can we engineer custom pigmentation patterns for skin, fur, feathers, scales, etc?

Approaches

♦genetic mods; ♦stem cells and bioprinting; neuroprosthetics

Expertise and consultation

♦dermatology; prosthetics; ornithology; herpetology; optics

References

Andreassen, M.L., Leeper, H.A., and MacRae, D.L. (1991). Changes in vocal resonance and nasalization following adenoidectomy in normal children: preliminary findings. J. Otolaryngol. *20*, 237–242.

Baier, D.B., Gatesy, S.M., and Jenkins, F.A. (2007). A critical ligamentous mechanism in the evolution of avian flight. Nature *445*, 307–310.

Barker, P.J., Hapuarachchi, K.S., Ross, J.A., Sambaiew, E., Ranger, T.A., and Briggs, C.A. (2014). Anatomy and biomechanics of gluteus maximus and the thoracolumbar fascia at the sacroiliac joint. Clin. Anat. N. Y. N *27*, 234–240.

Biewener, A.A. (2011). Muscle function in avian flight: achieving power and control. Philos. Trans. R. Soc. Lond. B. Biol. Sci. *366*, 1496–1506.

Brooke, M. (2018). Far from Land: The Mysterious Lives of Seabirds.

Butler, P.J. (2016). The physiological basis of bird flight. Philos. Trans. R. Soc. Lond. B. Biol. Sci. *371*.

Chin, D.D., and Lentink, D. (2017). How birds direct impulse to minimize the energetic cost of foraging flight. Sci. Adv. *3*, e1603041.

Crook, T.C., Cruickshank, S.E., McGowan, C.M., Stubbs, N., Wakeling, J.M., Wilson, A.M., and Payne, R.C. (2008). Comparative anatomy and muscle architecture of selected hind limb muscles in the Quarter Horse and Arab. J. Anat. *212*, 144–152.

Dial, K., and Biewener, A. (1993). PECTORALIS MUSCLE FORCE AND POWER OUTPUT DURING DIFFERENT MODES OF FLIGHT IN PIGEONS (COLUMBA LIVIA). J. Exp. Biol. *176*.

Di-Poï, N., and Milinkovitch, M.C. (2016). The anatomical placode in reptile scale morphogenesis indicates shared ancestry among skin appendages in amniotes. Sci. Adv. *2*, e1600708.

Doane, C.J. (2011). TACKING UPWIND: How An Albatross Flies To Windward.

Duriez, O., Kato, A., Tromp, C., Dell'Omo, G., Vyssotski, A.L., Sarrazin, F., and Ropert-Coudert, Y. (2014). How Cheap Is Soaring Flight in Raptors? A Preliminary Investigation in Freely-Flying Vultures. PLOS ONE *9*, e84887.

Farris, D.J., and Sawicki, G.S. (2012). The mechanics and energetics of human walking and running: a joint level perspective. J. R. Soc. Interface *9*, 110–118.

Finkelstein, Y., Wolf, L., Nachmani, A., Lipowezky, U., Rub, M., Shemer, S., and Berger, G. (2014). Velopharyngeal Anatomy in Patients With Obstructive Sleep Apnea Versus Normal Subjects. J. Oral Maxillofac. Surg. *72*, 1350–1372.

Galván, I., and Solano, F. (2016). Bird Integumentary Melanins: Biosynthesis, Forms, Function and Evolution. Int. J. Mol. Sci. *17*.

References

Grandin, T., and Deesing, M. (2014). Grandin, T. and Deesing, M.J. (Editors) 2014. Genetics and the Behavior of Domestic Animals, 2nd Edition, Academic Press (Elsevier) San Diego.

Häkkinen, K., and Häkkinen, A. (1991). Muscle cross-sectional area, force production and relaxation characteristics in women at different ages. Eur. J. Appl. Physiol. *62*, 410–414.

Hedrick, T.L., Tobalske, B.W., and Biewener, A.A. (2003). How cockatiels (Nymphicus hollandicus) modulate pectoralis power output across flight speeds. J. Exp. Biol. *206*, 1363–1378.

Lindsey, T. (2008). Albatrosses (Csiro Publishing).

Lohmander, A., Persson, C., and Owman-Moll, P. (2002). Unrepaired clefts in the hard palate: speech deficits at the ages of 5 and 7 years and their relationship to size of the cleft. Scand. J. Plast. Reconstr. Surg. Hand Surg. *36*, 332–339.

McNab, B.K. (2012). Extreme Measures: The Ecological Energetics of Birds and Mammals (University of Chicago Press).

Milenkovic, P.H., Yaddanapudi, S., Vorperian, H.K., and Kent, R.D. (2010). Effects of a curved vocal tract with grid-generated tongue profile on low-order formants. J. Acoust. Soc. Am. *127*, 1002–1013.

de Monsabert, B., Rao, G., Gay, A., Berton, E., and Vigouroux, L. (2017). A Scaling Method to Individualise Muscle Force Capacities in Musculoskeletal Models of the Hand and Wrist Using Isometric Strength Measurements. Med Biol Eng Comput *55*.

Nachmani, A., Aizenbud, D., Berger, G., Berger, R.L., Hazan-Molina, H., and Finkelstein, Y. (2013). The prevalence of platybasia in patients with velopharyngeal incompetence. Cleft Palate-Craniofacial J. Off. Publ. Am. Cleft Palate-Craniofacial Assoc. *50*, 528–534.

Nachmani, A., Aizenbud, D., Nageris, B., Emodi, O., and Kassem, F. (2017). Craniofacial structure variations in patients with palatal anomalies and velopharyngeal dysfunction. J. Craniomaxillofac. Surg. *45*, 203–209.

Niebergall, A., Zhang, S., Kunay, E., Keydana, G., Job, M., Uecker, M., and Frahm, J. (2013). Real-time MRI of speaking at a resolution of 33 ms: Undersampled radial FLASH with nonlinear inverse reconstruction. Magn. Reson. Med. *69*, 477–485.

O'Brien, T.D., Reeves, N.D., Baltzopoulos, V., Jones, D.A., and Maganaris, C.N. (2010). In vivo measurements of muscle specific tension in adults and children. Exp. Physiol. *95*, 202–210.

Parrott, G.C. (1970). Aerodynamics of Gliding Flight of a Black Vulture Coragyps Atratus. J. Exp. Biol. *53*, 363–374.

Pourmomeny, A.A., and Asadi, S. (2014). Management of synkinesis and asymmetry in facial nerve palsy: a review article. Iran. J. Otorhinolaryngol. *26*, 251–256.

Provini, P., Tobalske, B.W., Crandell, K.E., and Abourachid, A. (2014). Transition from wing to leg forces during landing in birds. J. Exp. Biol. *217*, 2659–2666.

References

Scanes, C.G. (2014). Sturkie’s Avian Physiology (Elsevier).

Shinohara, H. (1999). The musculature of the mouse tail is characterized by metameric arrangements of bicipital muscles. Okajimas Folia Anat. Jpn. *76*, 157–169.

Singh, A.P., and Nüsslein-Volhard, C. (2015). Zebrafish Stripes as a Model for Vertebrate Colour Pattern Formation. Curr. Biol. *25*, R81–R92.

Slominski, A., Wortsman, J., Plonka, P.M., Schallreuter, K.U., Paus, R., and Tobin, D.J. (2005). Hair Follicle Pigmentation. J. Invest. Dermatol. *124*, 13–21.

Stevens, K.N. (2000). Acoustic Phonetics (MIT Press).

Than, K. (2007). Why Bats Are More Efficient Flyers Than Birds.

Thomas, A.L.R. (1997). On the Tails of Birds. BioScience *47*, 215–225.

Tian, X., Iriarte-Diaz, J., Middleton, K., Galvao, R., Israeli, E., Roemer, A., Allyce Sullivan, Song, A., Swartz, S., and Breuer, K. (2006). Direct measurements of the kinematics and dynamics of bat flight. Bioinspir. Biomim. *1*, S10.

Usherwood, J.R., Hedrick, T.L., McGowan, C.P., and Biewener, A.A. (2005). Dynamic pressure maps for wings and tails of pigeons in slow, flapping flight, and their energetic implications. J. Exp. Biol. *208*, 355–369.

VisibleBody (2015). Human Anatomy Atlas 7.4.01.

Ward, S., Bishop, C.M., Woakes, A.J., and Butler, P.J. (2002). Heart rate and the rate of oxygen consumption of flying and walking barnacle geese (Branta leucopsis) and bar-headed geese (Anser indicus). J. Exp. Biol. *205*, 3347–3356.

Wikipedia (2012). Skin.

Wikipedia (2017). Psittacofulvin.

Wikipedia (2018a). Great frigatebird.

Wikipedia (2018b). Melanin.

Wikipedia (2018c). Carotenoid.

Wikipedia (2018d). Structural coloration.

Williamson, M., Dial, K., and Biewener, A. (2001). PECTORALIS MUSCLE PERFORMANCE DURING ASCENDING AND SLOW LEVEL FLIGHT IN MALLARDS (ANAS PLATYRHYNCHOS). J. Exp. Biol. *204*.

Xu, Y., Yang, C., Schreuder, W.H., Shi, J., Shi, B., Zheng, Q., and Wang, Y. (2014). Cephalometric analysis of craniofacial morphology and growth in unrepaired isolated cleft palate patients. J. Cranio-Maxillofac. Surg. *42*, 1853–1860.

References