Newsletter for August 2023

……

In this issue:

- Feasibility study: fur and overheating
- New developments in the developmental biology of scales
- Specifications for engineering implantable fur

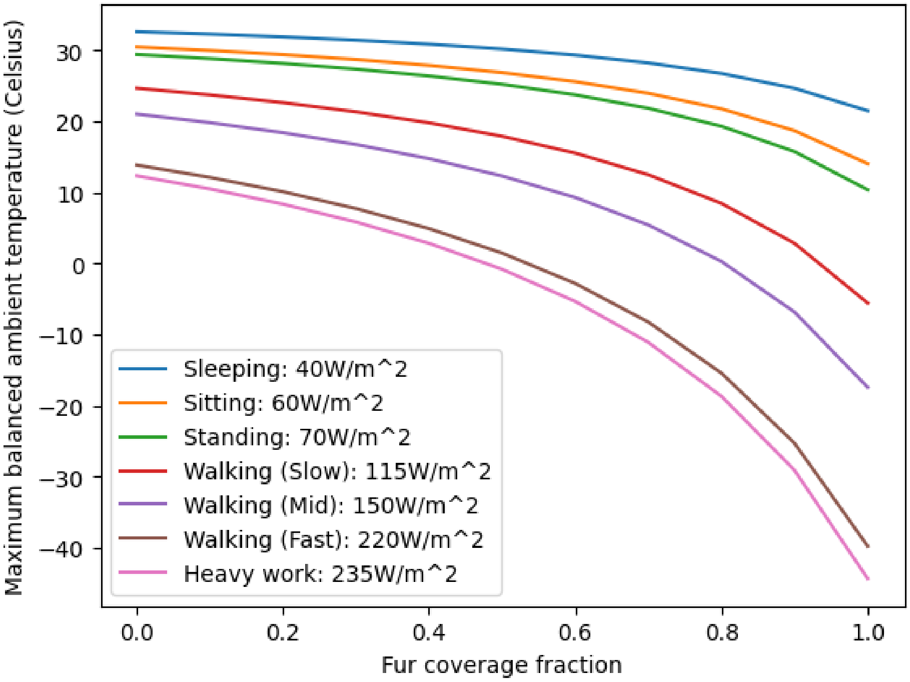
……

Feasibility study: fur and overheating

By Lathreas

Here’s a little sneak-peek of some things we are working on, with relation to heat transport of fur! It’s far from fully finished yet, but it should give some preliminary insights into what we can expect from fur and how much overheating would be a problem, which we can then use to anticipate engineering decisions for the design of implantable fur.

After all, fur is highly insulative, and anecdotal evidence shows that heat stroke can occur when wearing warm suits (such as fursuits) for too long. Since true fur, although perhaps not as insulative as a thick fursuit, would be “worn” permanently, we must carefully analyze the risk of overheating to prevent this from having adverse effects. How much fur can we really add to a person? And are there any strategies we can use to mitigate the lack of heat flow?



To at least partially answer these questions, we have taken a few sessions to draft a rough model of the heat transport between a human being and the environment, with various amounts of fur coverage. Please note that this is just a very simple model — it does not yet cover heat transport through sweating, for example, and furthermore ignores internal heat circulation through tissues. Instead, we aim to get a back-of-the-envelope calculation to derive some sort of “worst case scenario,” to get a picture of the order of magnitude of extra cooling we will roughly need to compensate for having fur. Future work will of course focus on the exact mitigation strategies, such as sweating or the addition of vascularized surfaces.

Under steady-state conditions, there is a certain ambient temperature that is perfectly suited to keep your body at 37 degrees Celsius. This only happens if the net heat accumulation in your body is exactly 0 watts. Since the human body generates its own heat — roughly 100 watts when idling, and up to more than 400 watts for sustainable exercise — there must be a net flow of roughly 100 to 400 watts away from your body to the environment. As such, the outside temperature needs to be lower than

Figure 1 (above): The predicted external temperature in which there is no net heating of the body, at different fur coverage levels. The left side of the graph corresponds to naked humans, and the right side of the graph corresponds to humans 100% covered in fur. Realistically, anthro creatures will not be 100% covered in the densest type of fur, as is modeled here, and as such, a fur coverage fraction less than 1.0 should be assumed for anthros. The simulation is run at 1.0 m/s wind speed, using dense fox fur, at various intensities of bodily activity. Note that for any value above a curve, sweating must be utilized to cool down. For example, a naked human doing heavy work (producing 235W/m^2) will start sweating when positioned in a room warmer than ~14 degrees Celsius. I'm currently working on adding sweating to the simulation. Future work will aim to uncover at which temperatures uncompensable heat stress occurs, which would give us a clear upper bound of the amount of fur we can add to a person.

your body to be able to expel heat through conduction or convection. Otherwise, the human body will heat up, and the only remaining strategy to cool back down is to use evaporative cooling, something humans excel at by sweating.

There is a certain temperature range in which your body can operate. A small decrease or increase in skin temperature may be uncomfortable, but since this also increases the net outflow of heat (through Newton's Law of Cooling), a new balance will be found where your skin temperature is slightly higher. By dilating and narrowing your veins, your body tries to keep your core temperature balanced at the cost of fluctuating your skin temperature. Of course, this has a limit: if your core temperature becomes too high, you will suffer heat stress, and if this is not compensated for, this leads to health damage. In this exercise, we are specifically interested in *uncompensable* heat accumulation, which is when your body has no more means to expel heat and will keep warming up indefinitely, leading to heat stroke and, after a while, to death. Uncompensable heat accumulation occurs when there is still a net influx of heat, even though your core and skin temperature is already at the limit of what it can withstand. Luckily, this means that our question becomes easier to answer from a modeling perspective: we just need to focus on the heat exchange between a skin surface that is already at its highest safe temperature (give or take 36.9 degrees Celsius), and ensure that in this state, the net accumulation of heat into the body is zero or negative.

To model this, we need to consider all ways in which heat can flow from your body to the environment. Heat exchange between humans and the environment occurs in four different ways: convective heat transport (air cooling), conductive heat transport (e.g. touching a cold floor), radiative heat transport (e.g. sunlight heating a body, but also the body radiating heat outwards), and evaporative cooling (e.g. sweating, panting). Importantly, these mechanisms occur both at the skin, which is the largest surface capable of cooling, and through breathing, which is called respiratory heat exchange.

Fur will necessarily impede on convective heat transport. In our simple model, we consider a human surface area (which is about 2 square meters), partially covered with dense fur, and partially naked. The percentage of skin covered in fur will change the amount of heat transport that can occur, and will shift which outside temperature remains balanced.

We're not quite ready to share detailed graphs yet, due to the fact that verification, analysis, and expansion of the model is required to get a fully realistic picture. After all, this is in a sense taking the "spherical cow" approach. It's very useful to get some preliminary ranges and results, but far from the complete picture, and only relevant to the exact research question asked. Take any data you see here with caution! Any model is only as good as its assumptions.

Here, you can see some of the model details, graphs, early results, and interpretations: heat_transport_of_spherical_furry.ipynb

Again, please note that these calculations completely ignore heat transport through sweating, both in the human and in the furry case, and as such is yet to be expanded fully. Furthermore, since this is the result of just a few sessions, we still need to verify the calculations and results to prevent calculational errors. Consider this a sneak-peak of sorts.

Should you find any mistakes, don't hesitate to let us know! And, if you think you can improve the model, please note that we have an opening for more advanced work over here: https://freedomofform.org/4977/project-lead-develop-a-model-of-heat-exchange-in-fur/ - we'd love your help!

New developments in the developmental biology of scales

By Lathreas

Growing scales on human skin is quite an involved task. We've explored some potential mechanisms of inducing scale-like growth on human skin in past updates, but of course, our investigations are still ongoing. There are many different areas to be tackled, such as untangling the genetic networks responsible for converting the epithelium's keratinization in reptiles, how individual scales manage to grow in careful patterns, and whether potentially analogous systems exist within humans that we can exploit for our purposes. We've been hindered for quite some time by the fact that the developmental biology of reptile scales remains a highly understudied field of research. There does exist plenty of research in the development of lizard limbs, but that is mostly due to their astounding regenerating capacities that most scientists are interested in.

But it seems that the long silence is now finally broken! Several papers that have been published in the last few months by other scientists have highlighted a key connection between the embryonic development of scales in snakes and the development of feathers in chickens (Tzika et al., 2023), and a preprint paper covers the development of scales in zebrafish in a similar fashion (Evanitsky and Di Talia, 2023), though of course a preprint still needs to pass peer review. Feather array development in chickens has a lot more coverage in scientific literature. Furthermore, it has been found that the development utilizes analogous pathways as those that exist in human skin pattern formation, such as the formation of fingerprints! (Glover et al., 2023)

Notably, the main driver behind symmetric pattern formation is the EDA/EDAR protein-receptor pair. EDA travels in a wavefront across a morphogenetic field, initiating Turing pattern formation during embryonic development of scales. Because this causes the scales to be formed sequentially, they will be perfectly stacked in a hexagonal grid, like stacking oranges. Seeing this system be conserved between so many different species allows us to draw many analogies between species. Some questions, mostly related to the downstream pathways as well as a molecular verification of the pathways, remain still. Let's see what future papers will bring!

Although of course we can't directly use the developmental pathways that occur during the embryonic stage due to the length-scale problem, this new information gives us a much more accurate view of how the gene networks overlap, and can give us some insight into which pathways we may exploit to give human skin tissue the properties of scales. We're not there yet, and we're not as far as with fur, but this does mark an important stepping stone for our analysis to continue!

Specifications for engineering implantable fur

By Lathreas

One of the keys towards engineering anything is to have a list of properties that it must adhere to. This is the same for engineering fur, feathers, or scales to be implanted or grown in humans. Knowing what exactly to change is half the battle!

Within the Integument Review project, we've been hard at work getting a comprehensive overview of the properties of the various types of integument, including that of humans, so that we know exactly what differs and what needs to be changed.

How would we even begin to obtain fur? Thankfully, in the case of fur, we're in luck. Humans already have hair, and as such, this is *technically* already fur. But of course, it looks nothing like the lovely coat that a fox or wolf or cat may have. One of the most obvious problems is that we don't have enough hair follicles. But beyond follicle count, the hairs themselves show significant differences in quality, ranging from differences in coloration, coloration patterning, length, width, to even how they interact with light itself to give the looks of fur. If we were to make a fur coat out of human hairs, even if the density is correct, it would look and feel nothing like the beautiful fur coats of most other mammals.

In order to convert human hair to an actual fur coat, we must recreate all relevant properties of fur. In principle, once all of these properties are changed, then the hairs are indistinguishable from a true fur coat, and as such, our aims have been achieved. Important here is that we do not care about the "implementation". Whether we use some fancy type of genetics, a simple peptide signal, or something as basic as a hair follicle transplant, the purpose of this list of properties is to have a clear checklist as to which changes we must tackle, and to verify whether a proposed method indeed solves our problem. In engineering terms, this is a specification requirement list, which is what any engineer should adhere to to clearly define the goal at hand. This leaves room for us to think out of the box while tackling many problems. For example, many of the "engineering challenges" of fur are already "solved" in humans, since humans already have fully functioning hair follicles.

This leaves us to focus only on the things that we need to change. After careful review of the different types of fur that exist within many non-human mammals, we have arrived at a clear and concise list of properties that should be modulated in single follicles to faithfully mimic a fur coat.

- Strand length
- Strand diameter
- Strand tapering shape (how thick is the base and how thin is the tip?)
- Strand curl
- Hair growth angle
- Strand flatness (eccentricity)
- Medullary index (the thickness of the inner core of a hair strand)
- Cuticle scale roughness (the roughness of the outside of a hair)
- Agouti patterning of pigments (banded patterns of eumelanin and pheomelanin)

At the ensemble level, there must additionally be at least two populations of fur, possibly three, to mimic the topcoat and undercoat of fur, with appropriate densities (at least tenfold increase compared to humans).

A detailed, engineering-focused explanation and motivation of each of these properties will be published in the first two chapters of the Integument Review report, which we are currently finalizing and making ready for publication.

Some of these properties will have a more dramatic impact than others. Of course, these would be strategic decisions that we can make based on this list. Importantly, we are now able to make these decisions deliberately, rather than implicitly making such choices due to being blindsided.

These bite-sized chunks are much more tangible for us to tackle. For example, the current Wnt project, led by Tiltwolf, aims to specifically modulate the width of human hair follicles, with the hopes of later being able to transplant these altered hair follicles back into a patient, potentially creating a viable undercoat (without running the risk of immune rejection that is present if we would use non-human follicles). This would tackle one of the bullet points in this list already. A similar signal target has been identified for modulating strand length, which could be our next project to tackle. Such projects would have to be done for each of these bullet points to fully reconstruct fur, and that would be all that is needed to get the job done. Still challenging, but not any more than what scientists are used to! This forms our main strategy of tackling any type of change, from fur, to feathers and scales, and even to things like anatomic changes.

We're currently hard at work wrapping up the final bits before we can publish the first few chapters of the Integumentary Review report. Once that is done, we can start looking forward to (hopefully) more wet-lab work to start messing with each of these properties.

Beyond fur, we've also made some great progress on the developmental biology of feathers and properties of scales, but more on that later!