Supplementary materials of "The nose is mightier than the tooth: larger male proboscis monkeys have smaller canines"

Ikki Matuda Danica J. Stark Augustine Tuuga
Senthilvel K. S. S. Nathan Benoit Goossens Carel P. van Schaik
Hiroki Koda

1 Model

The aim of the simulations part is to test our hypothesis for the explanations of positive/negative correlations among body mass and canine size by mathematical way. The previous research usually divided the subadult class of males from full adult males based on the nasal maturations as well as fully developed body size [6]. In the other words, the two stages likely exist, and status change likely corresponds with the developmental upgrades from subadult to adults. Therefore, before acquisition of harem status, young males would reach nearly to limitations of body mass under the circumstances that body mass cannot increase without status change. Here, we simply suppose the two stages model of developments, i.e., the primary developments of body mass and canine, and secondary process of body mass and nose size only after getting a harem status.

1.1 Primary development of body mass and canine

The body mass, m, basically develop under the assumptions that the growth rate depending on the body mass at the time, until reaching up to the developmental limitations, K, through the fixed time, T, i.e.,

$$\frac{dm}{dt} = am(1 - \frac{m}{K}) \quad \forall t \in [0, T], \tag{1}$$

where $a = const.$ is the shape factor to determine the sigmoidal curve of developments. This is based on the basic idea of body mass development model previously proposed [1, 3], and we further modified it considering the simple constrain of K. By contrasts, the canines develop in the later stage of body mass development. Here we suppose that the larger canines would reduce the feeding efficiencies [2], resulting in the reduce of the growth rates of body mass.

$$\frac{dm}{dt} = (1 - cz)am(1 - \frac{m}{K}), \tag{2}$$

where cz is the reducing factor determined by the cost factor $c \in [0, 1)$ and the size of canines z, and $cs < 1$ always holds. For model simplification, the canines start to develop at the time t_0, and linearly develop until $t_1 \leq T$.

$$z = \alpha(t - t_0) \quad (t_0 \leq t \leq t_1), \tag{3}$$

where $\alpha > 0$ is the growth rate of canine. Consequently, the differential equation of the body mass in $t \in [0, T], T > t_1$ is:

$$\frac{dm}{dt} = \begin{cases} am(1-\frac{m}{K}) & (0 \le t \le t_0) \\ \{1 - c\alpha(t-t_0)\}am(1-\frac{m}{K}) & (t_0 \le t \le t_1) \\ (1-cz_1)am(1-\frac{m}{K}) & (t_1 \le t \le T). \end{cases} \tag{4}$$

where $cz_1 := cz_{t=t_1} = c\alpha(t_1 - t_0)$, because the monkey likely develop body mass until $t = T$, with the constant of the reducing factor, after terminating the canine growth ($t = t_1$). Note that $0 \le z \le \alpha(T - t_0)$ holds; therefore,

$$\alpha \le \frac{z}{T - t_0} \tag{5}$$

also holds.

In case of $t < t_0$, i.e., before the onset of canine eruptions, the equation is a simple logistic equations; therefore the solutions are,

$$m(t) = \frac{K}{1 + A_0 e^{-at}}, \tag{6}$$

where A_0 is the constant determined by the initial values of $m(0) = m_0 > 0$, as follows:

$$A_0 = \frac{K}{m_0} - 1. \tag{7}$$

Once the canine begins to develop, i.e., in the case of $t_0 \le t \le t_1$, the differential equations are solved as follows;

$$\frac{dm}{dt} = \{1 - c\alpha(t - t_0)\}am\frac{K-m}{K} \tag{8}$$

$$\int \frac{K}{m(K-m)}dm = a\int \{1 - c\alpha(t-t_0)\}dt \tag{9}$$

$$\int \{\frac{1}{m} + \frac{1}{(K-m)}\}dm = a\int \{1 - c\alpha(t-t_0)\}dt \tag{10}$$

$$-ln|\frac{K-m}{m}| = -\frac{1}{2}ac\alpha t^2 + a(1 + c\alpha t_0)t + C \tag{11}$$

$$m(t) = \frac{K}{1 + A_1 e^{\frac{1}{2}ac\alpha t^2 - a(1+c\alpha t_0)t}}. \tag{12}$$

Then, after terminating the canine developments ($t = t_1$), we found the solutions are simply:

$$m(t) = \frac{K}{1 + A_2 e^{-a(1-cz_1)t}}. \tag{13}$$

Note that the following equations must be satisfied,

$$m(t_0) = \frac{K}{1 + A_0 e^{-at_0}} = \frac{K}{1 + A_1 e^{\frac{1}{2}ac\alpha t_0^2 - a(1+c\alpha t_0)t_0}} \tag{14}$$

$$m(t_1) = \frac{K}{1 + A_1 e^{\frac{1}{2}ac\alpha t_1^2 - a(1+c\alpha t_0)t_1}} = \frac{K}{1 + A_2 e^{-a(1-cz_1)t_1}}. \tag{15}$$

Consequently, the basic models for body mass are;

$$m(t,t_0,t_1,K,a,c,\alpha,A_0,T)=\begin{cases}\frac{K}{1+A_0e^{-at}} & (0\le t\le t_0)\\ \frac{K}{1+A_0e^{\frac{1}{2}ac\alpha t_0^2+\frac{1}{2}ac\alpha t^2-at(1+c\alpha t_0)}} & (t_0\le t\le t_1)\\ \frac{K}{1+A_0e^{\frac{1}{2}ac\alpha t_0^2-\frac{1}{2}ac\alpha t_1^2-at+ac\alpha t_1t-ac\alpha t_0t}} & (t_1\le t\le T),\end{cases} \tag{16}$$

and those for canine size are;

$$z(t,t_0,t_1,\alpha,T)=\begin{cases}0 & (0\le t\le t_0)\\ \alpha(t-t_0) & (t_0\le t\le t_1)\\ \alpha(t_1-t_0) & (t_1\le t\le T).\end{cases} \tag{17}$$

1.2 Rank-dependent secondary development of body mass and nose

Our data suggested that males who acquire the harem alpha status develop the nose as the badge of status, coordinated with body mass. Here, we suppose that males who acquire the harem alpha status can dominate the copulation opportunities as well as *foraging resources*, because harem group defend their territories together with females. Harem males can continue the growth of the body mass after the primary developmental process complete, while males who cannot get harem stop the body mass growth. Then, the differential equations of the body mass in the secondary development for harem males are equivalent with (4), i.e.,

$$\frac{dm}{dt}=(1-cz_1)am(1-\frac{m}{K})\quad (t\ge T) \tag{18}$$

while those for non-harem males are:

$$\frac{dm}{dt}=(1-cz_1)\{a-\frac{t-T}{t_2-T}a\}m(1-\frac{m}{K})\quad (t\ge T). \tag{19}$$

where, t_2 is the termination time of the body mass growth. This equation is solved as the similar way of (8) - (12),

$$\begin{aligned} m(t,t_0,t_1,K,a,c,\alpha,A_0,T,t_2) &= \frac{K}{1+A_3e^{\frac{1}{2}\beta t^2-\beta t_2t}} && (20)\\ A_3 &= A_0e^{\frac{ac\alpha(t_0^2-t_1^2)}{2}-aT+ac\alpha T(t_1-t_0)-\beta T(\frac{1}{2}T^2-t_2T)}, && (21)\end{aligned}$$

where $\beta := \frac{a(1-c\alpha t_1+c\alpha t_0)}{t_2-T}$. Based on the our observations with the previous notion for allometric development of ornament size with body mass, we suppose that the nose size is primary determined by the body mass.

2 Simulations

2.1 Overview of aims

Our motivation of the model simulation is to know how the termination time of canine development, t_1, determines the results of the final body mass and canine size. We simulated the growth pattern based on several deterministic parameters, considering the developmental evidences of the probocsis monkeys.

2.2 Parameter proposals

First, the time parameter is normalized at the primary maturation time T, i.e., $T := 1$. Therefore, t_0, t_1 and t_2 are the time relative to the maturation time, T. By definition, $0 \le t_0 \le t_1 \le T = 1 \le t_2$ holds. Additionally, the maximum canine size z is also normalized to 1 at the case where the monkey maximumly develop the canine during the periods between t_0 and $T = 1$. Following (3), $\alpha = \frac{1}{1-t_0}$.

Next, we supposed that the age ($t = T = 1$), where males reach to limitations as a adult class, is around 8 yrs, based on the observation studies (Matuda personal com or [5]). Until these periods, nose enlargement is not typically started yet [6]. For the onset of the canine developments, we refer some developmental evidence of *Cercopithecus* [4] and very early report on proboscis monkeys [7], in which canines start to develop from around 4 years, and lasted until 8 years for both males and females. Therefore, the onset time of canines developments will be supposed as 4 yrs, the half of the subadult maturation time, i.e., $t_0 = \frac{1}{2}$.

Possible records for body mass were used for the parameters in the simulations. The body mass at the birth was reported as 0.45kg [7], and the maximum body mass of our observation is 25.5 kg and 10 kg for male and female, respectively. Therefore, we set $m(0) = 0.45$, $K_{male} = 25.5$, and $K_{female} = 10.0$. Additionally, we used the body mass record around 4 years old, at the onset time of the canine eruptions. The body mass at the canine eruptions would be around 6.5 kg (Matuda pers. comm. and records in Japan Monkey Center). Therefore we set $m(\frac{1}{2}) = 6.5$ in the simulations. Finally we supposed the development of body mass would terminate within one year after the maturation time, T; therefore $t_2 = \frac{9}{8} = 1.125$.

Based on these parameter proposals above, we simulated the body mass at the time when monkeys fully develop. Here we tried to simulate/evaluate $m(2)$, body mass around 16 years olds, with the various combinations of cost parameters and canine termination times, i.e., $c \in (0, 1)$ and $t_1 \in (0.5, 1)$

3 Results of simulations

Figure 1 showed the simulated results of developmental growth curves for harem alpha status males, non-alpha status males, and females with various cost and termination time parameters. Our simulations showed that strong cost by canine development influence the body mass growth of males. For males, body mass vary depending on the termination time of canines, i.e., canine size. By contrast, the body mass of females are relatively independent of the termination time of canine, i.e., canine size.

In case of the no/weak costs by canines, body mass of males and females are independent of termination times of canine, i.e., canine size. Thus, in the terms of qualitative discussion. large cost by canine size influence the body mass development, particularly for males (see Figure 2).

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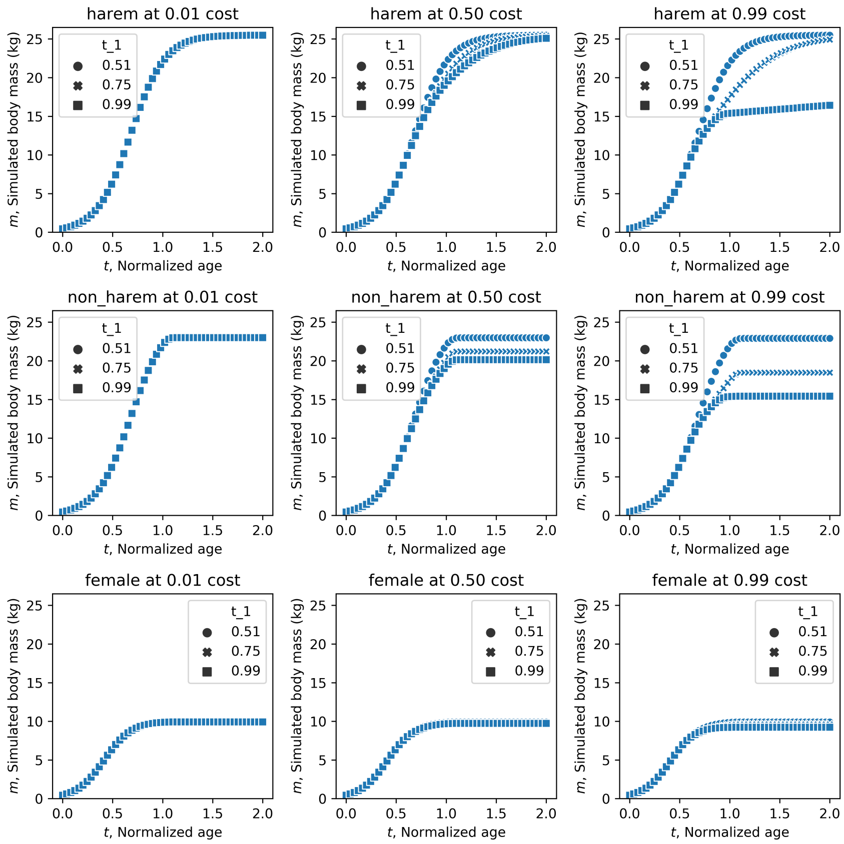

Figure 1: Developmental growth curves for females, non-harem males, and males. The cost parameters ranged between 0.01(almost no cost), 0.5(moderate), and 0.99 (strong cost). The terminations of canine development were set at each of 0.51 (immediate termination), 0.75 (middle), and 0.99 (maximum canine growth).

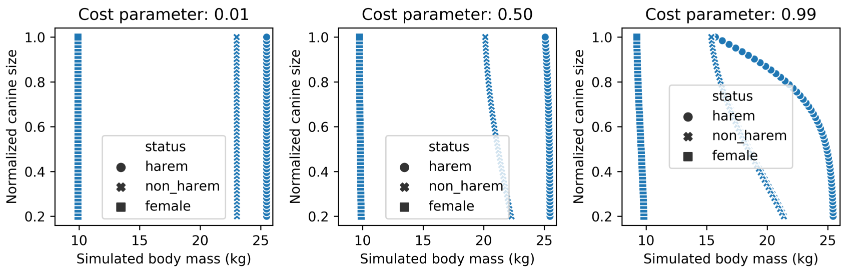

Figure 2: The relationships of normalized canine size and body mass at the final developmental stages, for simulated harem alpha status males, non-alpha status males, and females.The left panel is the simulation of weak cost parameter ($c = 0.01$), middle is that of moderate ($c = 0.5$), and right is of strong ($c = 0.99$). In case of strong cost parameter, the negative correlations between body mass and canine size were observed for both statuses of males, but not or weak in females, which are consistent with our observations.