Morphological Animal Design: Parameterized Quadrupedal Anatomy and Locomotion

Niklaus Houska
Computational Robotics Lab, ETH Zurich

***Abstract*—The project introduces an animation skeleton to create arbitrary quadrupeds and how to auto-generate walk animations for them. The skeleton captures the relevant anatomical traits from small dogs to African elephants and is parameterized by the location and size of the joints. Furthermore, a parameterization of the walk locomotion of digitigrades and unguligrades is introduced. A visually viable walk motion is constructed from an existing reference motion under the assumption of dynamic similarity.**

I. Introduction

The core interest of the project is to explore how animal anatomy influences animal movement - with a focus on quadruped mammals. Sharing a common ancestor millions of years ago, lifeforms have since evolved to form today's species diversity - optimizing their bodies to specific life styles. The ability to move constitutes a major factor in an animals survivability and drove evolutionary change. The aim of the project is to provide a tool, in which different anatomies can be quickly prototyped and their respective movement observed.

The first part of the work introduces a parameterization of the animal skeleton and provides implementation details on how the geometric representations of different skeletons are built using a single virtual armature. The second part describes the parameterization of the walk gait and how to infer viable parameter values from a reference animal using the notion of geometric and dynamic similarity.

II. Animal Model

Quadrupeds walk on four legs and share the same principle bone structure. Regarding locomotion the major classification is the foot posture (In Figure 1). *Plantigrades* put their whole foot on the ground, such that the heel touches the ground. Prominent examples are bears, primates and many reptilians. This maximizes stability and weight-bearing capabilities, but limits speed, as legs are shorter and heavier at the far end. *Digitigrades* on the other hand only put their toes on the ground and have the heel up in the air, allowing them to move more quickly and quietly than most other animals while still providing a stable foothold. Thus, predators such as canids and cats are digitigrades. Lastly, *unguligrades* walk on the tips of their toes and are usually equipped with hoofs. Typically, unguligrades are herbivores, examples are horses, cattle, rhinoceros and deer. [1] [2]

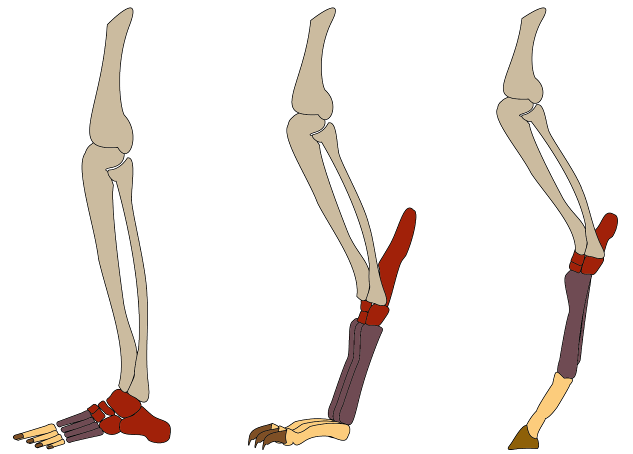

Figure 1. Foot posture of different locomotion types. From left, plantigrade, digitigrade, unguligrade. In red: tarsus which includes the heel, in purple: metatarsus, in yellow: toes, in brown: nails, claws and hoofs. Image downloaded from https://fr.wikipedia.org/wiki/Digitigrade October 2020.

A. General Skeleton

In this work, the skeleton of an animal is described by its joint locations and end points (i.a. toe tip and tail) in a relaxed standing position, to which is referred to as *rest pose*. An additional size parameter per location defines the width of the connecting bones. The full model is depicted in Figure 2. This section explicates the design choices and abstractions made.

1) Hindlimbs: The feet are modeled with two bones - a single toe and the metatarsus. The tarsus as seen in Figure 1 is thereby fused with the metatarsus because they are connected with a static joint. The foot connects via the ankle joint to the lower leg, which anatomically consists of the tibia and fibula. The role of the fibula is to stabilize the ankle joint [3]. The lower leg is connected via the knee to the upper leg - the femur - which connects to the pelvis. Altogether, the hindlimb consists of four bones, the femur, tibia, metatarsus and toe, and is parameterized by five locations, the hip, knee, ankle, MTP and the tip of the toe.

2) Spine and Rib Cage: The spine is made up of five parts. The cervical vertebrae make up the neck. The body is made up by thoracic and lumbar vertebrae, where the thoracic are connected to the ribs and the lumbar lie between the former and the pelvis. The sacral vertebrae wrap around

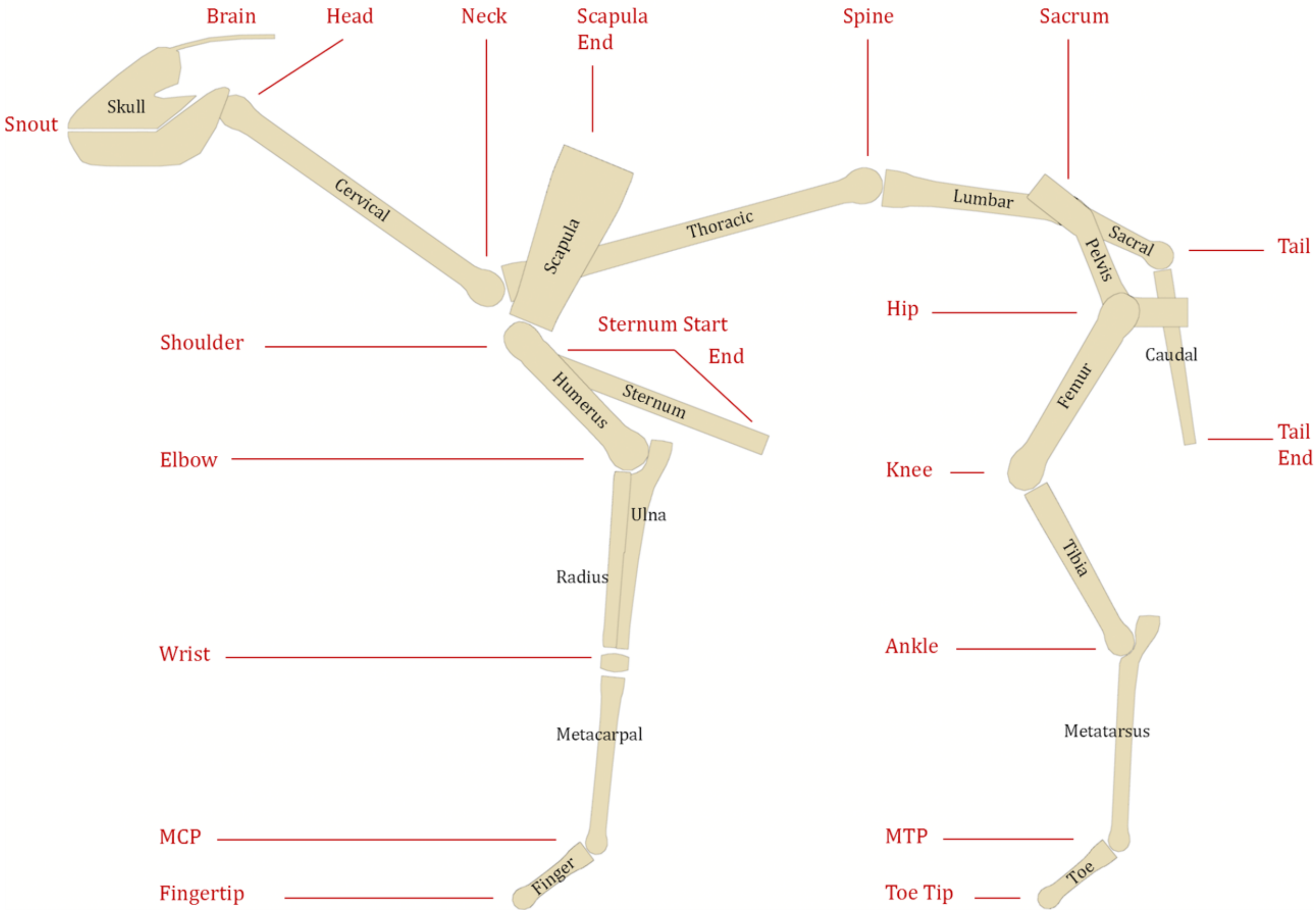

Figure 2. The animal model. The skeleton is configured to a camel's *rest pose*. In black: the bone names. In red: locations defining the parameters of the model. Each location except the snout and brain hold an additional size parameter. In total the model is made up by 40 parameters - 21 locations and 19 sizes. The ground beneath the center of the two hip joints forms the origin of the coordinates.

the pelvis, while the caudal vertebrae form the tail. The ribs connect the thoracic vertebrae to the sternum building the rib cage. In other animals the number of vertebrae can vary greatly and the distinction is insignificant for the purpose of locomotion [4]. Thus, the parameterization consists of the five spine bones described by six locations plus the start and end location of the sternum.

3) Pelvis: The shape and relative positioning of the pelvis differs greatly in other animals, but always articulates with the hip joints and the sacrum - and having these values already parameterized requires no further parameter.

4) Shoulder: The shoulder is a ball-and-socket joint where the upper arm, called the humerus, articulates with the shoulder blade, i.e. scapula. The scapula is a triangular shaped bone posterolateral to the rib cage and responsible of moving the shoulder. Animals that are able to climb or fly typically have a strongly developed clavicle that articulates with the sternum adding stability but restricting shoulder movement. On contrast, animals adapted to running show an underdeveloped clavicle leading to forelimbs that are disconnected from the rest of the skeleton, which allows the scapula to function as an extension to the arms and enables the animal to take longer strides [5]. The presented general skeleton omits the clavicle.

5) Forelimbs: Forelimbs work similar to the hindlimbs, with the addition of the scapula. The forelimb's five bones from below up are finger, metacarpal, ulna, humerus and scapula and are parameterized by the four joints MCP, wrist, elbow and shoulder plus the locations where the finger and scapula end. The ulna together with the radius constitute the lower arm anatomically and generally enable full longitudinal rotation. During locomotion the two bones always cross and the detail is for the purpose of analyzing gaits insignificant.

6) Skull: Although having no direct impact on locomotion, for completion a simple parameterization of the skull is achieved with two relative locations. The first location determines the size of the cranial bones, which hold the brain, while the second location defines the extend of the facial bones making up the snout.

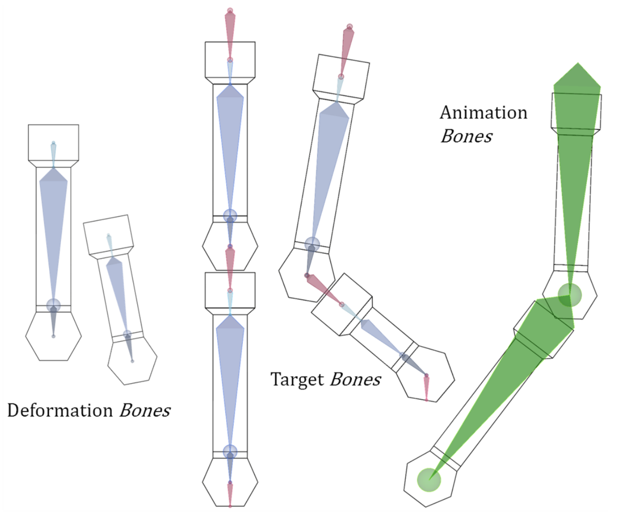

Figure 3. Visualization of the three levels of the virtual armature. The deformation *bones* mutating the mesh are in blue. The target *bones* controlling the deformation *bones* are in red. The final animation *bones* built based on the target *bones*' location are in green.

B. Implementation

The general skeleton is implemented using rigging techniques from computer animation. A polygon mesh builds the surface representation of the anatomical components and a virtual armature animates and mutates the mesh. To avoid confusion, the term *bones* in cursive will refer to the interconnected parts making up the rig of the virtual armature. The presented model works in three levels visualized in Figure 3 and described below.

1) Deformation Bones: The virtual armature of a simple mesh representing an anatomical bone consists of three *bones* named *head*, *body* and *tail* (Figure 3, highlighted in blue). Inverse kinematics are used to specify start and end location of this *bone* chain. The relative rotations of *body* and *tail* are constrained to zero but *body* is allowed to stretch, keeping them in a straight line.

2) Target Bones: The individual anatomical parts are connected by target *bones* (Figure 3, highlighted in red) that control the position of the deformation *bones*. Furthermore, the connected *head* and *tail bones* inherit the target *bone*'s scale, which enables the control of the width of the mesh. The position and scale of these target *bones* represent the parameters of the general skeleton (Figure 2, the names in red).

3) Animation Bones: The actual animation rig is build based on the positions of the target *bones* and used to create the walk animation (Figure 3, highlighted in green). Every time a target *bone* is moved, i.e. the animation rig *bones* needs to be rebuild.

III. Walk Animation

Animals vary in size, but move in similar ways; they walk to go slowly, trot at intermediate speeds and if possible gallop to go fast. Mice move with high step frequency and bent limbs, while elephants take longer but fewer steps with straightened legs. To understand these important differences as well as similarities, some basic principles introduced in [6] are summarized next.

Table I
Locomotion Terminology

Term	Description
Stride	Distance covered between two successive initial contacts of a given leg
Step Length	Distance covered between the initial contacts of the left and the right leg
Duty factor	Percentage of the stride a given leg contacts the ground
l	Height of the hip joint in *rest pose*
t	Time of a full stride
$f := 1/t$	Cadence as strides per second
$v := f \times$ stride	Movement speed
$r := f/$stride	Walk ratio
Froude no. $:= v^2/lg$	Predicts change of gait: 0-0.8 (Walk), 0.3-3 (Trot), 2+ (Gallop). $g \approx 9.81$ is gravity
Strouhal no. $:= fl/v$	Constant in *dynamically similar* cyclic motions.

A. Similarities

1) Geometric Similarity: If a shape becomes identical to another by multiplying all length dimensions by a factor λ, then they are geometrically similar. Geometric similarity between two animals implies that they have areas proportional to (length)^2 and volumes ($\simeq$ masses) proportional to (length)^3.

2) Dynamic Similarity: Extending the idea of geometric similarity, a motion is dynamically similar to another if they are made identical by multiplying all length dimensions by λ, all times by τ and all forces by ϕ. Direct derivations of dynamic similarity are that all velocities are multiplied by λ/τ and accelerations by λ/τ^2, from there it can be shown that two motions subject to gravity can only be dynamically similar if the quantity v^2/lg is equal, called the Froude number (See Table I). This number serves as a predictor of the speed an animal changes gait. A hypothese formulated by Alexander and Jayes (1983) states, that where possible, animals walk in dynamically similar manners, implying that they will change gaits at an equal Froude number. Furthermore, in dynamically similar cyclic motions the Strouhal number fl/v is constant.

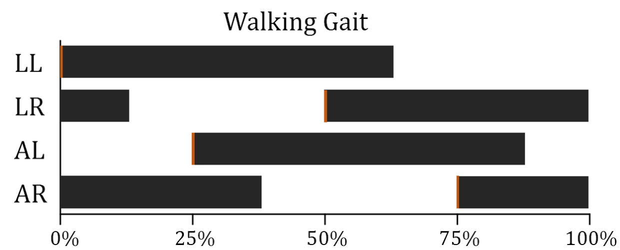

Figure 4. Footfall pattern at walk with duty factor of 62.5%. Orange lines mark the initial contact, black indicates times of contact. Bottom axis is % of cycle. LL: left leg, LR: right leg, AL: left arm, AR: right arm.

B. Walk Parameterization

Animals use the walk gait to move slowly. It is an asymmetrical gait with a footfall pattern depicted in Figure 4. This section explicates how the individual parts of the walk cycle are understood and parameterized and then how appropriate values are found based on the insights from dynamic similarity. Figure 7 depicts the resulting motion for seven different animals. To describe a motion in computer animation, the location and rotation of animation *bones* are stored for a few key moments, called keyframes, and smoothly interpolated in between. In a cyclic motion the first and last keyframe coincide.

1) Up and Down Movement: The pelvis goes up and down during each step. The lowest position is reached after one leg made contact and before the other gets lifted up, during which the weight is evenly carried by both legs setting the hip joints level. The highest position is reached after the lifted leg has passed and the weight supporting leg pushes the body forward. Consequently, the pelvis is dragged down by the lifted leg and pushed by the other, making it askew. The situation is visualized in Figure 5. Formally,

$$t_{\text{up, left}} = t_{\text{contact, left}} + 0.6 \times (\text{duty factor}) \times t$$
$$t_{\text{down, left}} = (t_{\text{up, right}} + t_{\text{up, left}}) \times 0.5$$

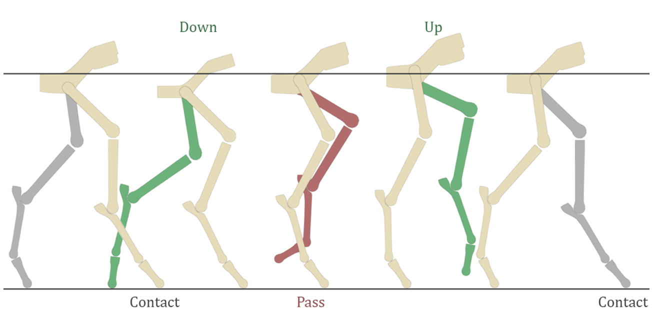

Figure 5. Up and down movement during a single step of the hindlimbs of a horse. The left leg is highlighted grey at the initial contacts, green at the up and down poses and red at the pass pose.

The forelimbs raise and lower the upper body with the same pattern, but shifted by $t/4$. In this work the height of the upper body is measured by the position of the neck joint (In Figure 2). The neck's bottom position coincides with the pelvis' top position and vice-versa. Furthermore, the head counter balances the swinging and follows the movement of the pelvis. The extend of the displacements are exposed as parameters relative to the height of the respective positions at *rest pose*; two offset values for each the pelvis, neck and head plus the roll rotation of the pelvis and the pitch rotation of the head.

2) Hindlimbs: The cycle of a leg has three key positions. The initial contact with the ground t_{contact}, the last contact with the ground t_{release} and the pass position t_{lifted} when the leg is in the air. The first two times are given by the footfall pattern, the last time is defined as

$$t_{\text{lifted}} = t_{\text{release}} + \frac{1}{3} \times (1 - \text{duty factor}) \times t$$

Assuming the animal walks along the positive y-direction and the origin is on the ground below the two hip joints, the positions of the toe tip are defined as:

$$\begin{aligned} p_{\text{contact}} &= (\pm x, (\text{duty factor}) \times \text{stride} \times (0.5 + s),\ 0) \\ p_{\text{release}} &= (\pm x, (\text{duty factor}) \times \text{stride} \times (-0.5 + s),\ 0) \\ p_{\text{lifted}} &= (\pm x,\ p_{\text{release},y} + 0.2 \times \text{stride},\ (\text{step height})) \end{aligned}$$

where x is the step width and $s \in [-0.5, 0.5]$ the center control ($s = 0$: hip as center). Thus, the first three parameters reveal as step width, center and height.

The end points of the leg for each of the three key positions are known, it remains to find the joint positions of the MTP, ankle and knee. This work presents a method that determines the positions using simple heuristics based on the known configuration of the *rest pose* and the natural anatomical constraints. The ankle and knee can not overextend, however the toe can move around the MTP joint. An observation from Figure 6 is that the angles relative to the ground α and β decrease at p_{contact} and increase at p_{release}.

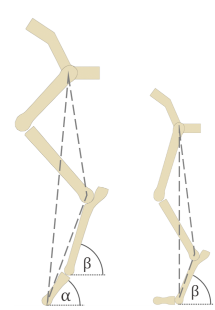

Figure 6. Leg configuration at *rest pose* of an unguligrade (left) and a digitigrade (right). α and β are the angles between the ground and the toe and metatarsus, respectively.

α_{contact} is equal to α for digitigrades and slightly lower for unguligrades. The decrease is modeled as a function of $\frac{\text{stride}}{l} \times C$, parameterized by C. β_{contact} is then selected, such that the triangle spanned by the hip, ankle and toe is closest

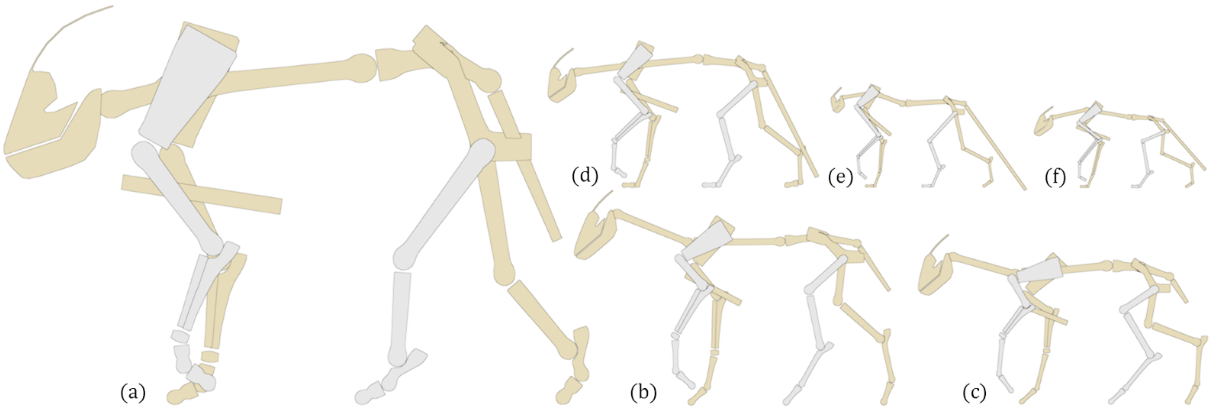

Figure 7. The walk motion of seven different animals. (a) African Elephant, (b) Horse, (c) Stag, (d) Lion, (e) Cheetah, (f) Wolf

to the one in the *rest pose* (See Figure 6). Lastly, if required β_{contact} is adjusted to comply with the anatomical constraints.

α_{lifted} is simply exposed as parameter, while β_{lifted} is not keyframed and thus interpolated between β_{release} and β_{contact}. Typically, animals bend the toe heavily backwards when lifted, therefore α_{lifted} is expected to be large.

The heuristic applied at p_{contact} is inaccurate at p_{release}, as it overestimates the increase of β. Principally, the rotational work required to touch p_{release} should be made by the knee and hip joint, rather than the ankle. Further, at p_{release} the toe "rolls off" elegantly and is typically in a vertical position, both in digitigrade and unguligrade locomotion. The adjusted heuristic capable of providing this configuration defines the angles as

$$\alpha_{\text{release}} = \alpha + R_1 \times (\alpha_{\text{lifted}} - \alpha)$$
$$\beta_{\text{release}} = \beta + R_2 \times R_1 \times (\alpha_{\text{lifted}} - \alpha)$$

where $R_1 \in [0, 1]$ and $R_2 \in \mathbb{R}_0^+$ are the parameters. α_{release} is interpolated with weight R_1 between α and α_{lifted} and R_2 controls the fraction of the delta rotation of α_{release} that is applied to β_{release}. For example, if the toe rotates 40 degrees, with $R_2 = 0.5$ the metatarsus will rotate 20 degrees. Finally, if needed β_{release} is adjusted to comply with the anatomical constraints.

Altogether, three parameters control the position of the foot (width, center and height), α_{lifted} gives the toe rotation while in the air and three additional parameters (C, R_1 and R_2) influence the heuristics that determine the joint locations.

3) Forelimbs and Scapula: In quadruped locomotion, the force pushing forward is exerted by the hindlimbs while the forelimbs move more elegantly. From a visual perspective, a reason for the elegance is that the arms always form an arc from the elbow down, i.e. the area spanned by the elbow, wrist, MCP and fingertip is convex. Different is that the metacarpal can rotate around the wrist joint, while the metatarsus can not overextend around the ankle. Apart from that, the forelimbs are constructed like the hindlimb. Lastly, the scapula adds another component to the forelimbs, but given the known positions of the wrist and scapula, the elbow and shoulder positions are correctly found using inverse kinematics. Furthermore, the scapula is allowed to move up and down relative to its parent, the neck. This constitutes a simplification of the movability of the scapula, however it is enough to find a viable arm configuration. The displacements are exposed as two parameters *up* and *down* and the respective times t_{up} and t_{down} coincide with the ones of the neck.

C. Parameter Values

The parameter values are calculated based on the known values of the walk animation of a reference animal by assuming geometric and dynamic similarity. Under this assumption, length dimensions are simply multiplied by λ and times by τ, defined as

$$\lambda = \frac{l}{l_{\text{ref}}} \qquad \tau = \sqrt{\lambda}$$

where $\tau = \sqrt{\lambda}$ is derived from the Froude numbers

$$v^2/lg = \left(\frac{\lambda}{\tau} v_{\text{ref}}\right)^2 / \lambda l_{\text{ref}} g$$

which as established are equal between dynamically similar motions. Parameters denoting angles and percentages are simply copied from the reference parameters.

IV. Discussion

The project presents a general animation skeleton that can model the basic anatomy of any quadruped. The skeleton of such an animal is described by the location and size of its joints in a relaxed standing position. This representation can be vectorized and interpreted as a point in a high-dimensional vector space, which allows mathematical analysis on a set of animals. However, it requires that the described pose is consistent among different configurations and a certain degree of care when constructing a new configuration by hand.

Furthermore, a parameterization of the walk locomotion is presented. This parameter space is relative to the configuration of the general animation skeleton and displays the power of the chosen representation. After knowing the parameters for a single animal, the walk parameters of others is calculated assuming dynamic similarity. Moreover, metrics to measure the anatomical similarity of two animals can be defined based on their vectorized representation, which in turn helps to choose the best reference motion. Finally, a viable walk animation is consistently found, both for digitigrade and unguligrade locomotion and is conveniently tweaked by changing the parameters manually.

The main contribution of this project is the modeling strength of the skeleton and walk parameterization, together with the possibility to quickly prototype new configurations and to observe their respective movement. As displayed in Figure 7 the model can accurately express the walk motion of a large set of real animals. On the other hand, the model has no physical foundation and can not guarantee the feasibility of a specific skeleton configuration or walk motion.

In future work, the support for plantigrade locomotion could be added. Also, it would be interesting to include the trot and gallop gait, in which case certain simplifications of the walk parameterization would need to be addressed, such as the movability of the scapula.

REFERENCES

[1] P. Myers, “Legs, feet, and cursorial locomotion,” 2020, accessed: 10.09.2020. [Online]. Available: https://animaldiversity.org/collections/mammal_anatomy

[2] A. F. Deblase and R. E. Martin, “A manual of mammalogy: With keys to families of the world,” vol. 436 pp., 2011.

[3] K. M. Gupton M, Munjal A, “Anatomy, bony pelvis and lower limb, fibula.” *StatPearls Publishing*, 2020, accessed: 10.09.2020. [Online]. Available: https://www.ncbi.nlm.nih.gov/books/NBK470591/

[4] T. E. of Encyclopaedia Britannica, “Vertebral column,” 2020, accessed: 11.10.2020. [Online]. Available: https://www.britannica.com/science/vertebral-column

[5] ——, “Clavicle,” 2009, accessed: 11.10.2020. [Online]. Available: https://www.britannica.com/science/clavicle

[6] R. M. Alexander, “Principles of animal locomotion.” Princeton University Press, 2003.