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# A Ground Reaction Forces estimation method to study non-human primate bipedalism out-of-the-lab

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## 1. Introduction

Studying occasional bipedalism in non-human primates is a fundamental line of research in functional anatomy, putting into perspective the emergence of habitual bipedalism in hominins and improves our knowledge on non-human primates locomotor capacities (Berillon et al. 2010). Most studies of bipedal locomotion in non-human primates are limited to video-based analyses of anatomical reference points in the sagittal plane, leading to 2D studies of segmental angles (Druelle et al. 2022).

Using biomechanical modeling for the study of non-human primates extends these analyses to 3D and enables to go beyond the kinematic study to estimate internal actions and muscle forces by inverse dynamics (Oku et al. 2021). Nevertheless, the study of bipedalism in primates is experimentally complex, due to the challenge to collect both Ground Reaction Forces (GRF) from monopodal supports, and a motion capture of the gait cycle during natural movements.

In this study, we aim to overcome this limitation by applying an optimization-based method for estimating GRF during bipedalism in olive baboons. This study paves the way for complete motion analysis for non-human primates into the wild.

## 2. Methods

### 2.2 Experimental data

Experimental data were collected at the Motion Analysis of Primates platform based at the CNRS Primatology Station. CTScan were acquired on an anesthetized olive baboon (*Papio anubis*) (Voxcan, Marcy-l'Étoile, France) and 3D reconstruction of the whole skeleton was made using the Amira software.

The baboon was 6 years old female and weighed 13.8 kg at the time of the experiment. It was trained to cooperate with the experimenters using positive reinforcement techniques, leading to an habituation of the baboon to the experimental setup (treadmill, sEMG, jacket, markers, cameras and computers). The individual was equipped with 40 external reflective markers placed on anatomical landmarks. An OptiTrack system (NaturalPoint Inc. USA) with 10 cameras captured bipedal locomotion realized on a treadmill. Motion capture was triggered when the baboon performed walking cycles. 7 regular cycles performed at a speed of 2.5km/h were used in this preliminary study, extracted from a larger dataset.

To assess the estimated GRF, experimental GRF were concurrently collected on another baboon female of 5.7 kg using a single force platform, during another campaign. All the procedures were approved by the

ethical committee on animal experimentation no. 14 (Project 68-19112012, CEEA-14 Marseille).

## 2.2 Baboon biomechanical model

A biomechanical model has been set up in the CusToM library (Muller et al. 2019), including subject specific geometric and inertial properties. The biomechanical foot model included mobile metatarsals and phalanges (Fig. 1 (a)). Ankle joints were universal with personalized axes and knee joints were hinges with personalized axes, hip joints were spherical.

## 2.3 GRF estimation method

After an inverse kinematics step, a GRF estimation method (Morin et al. 2024) has been adapted to the current problem. Each foot was mapped with  $N_c = 15$  contact points, considering baboon contact specificities (front of the calcaneum, metatarsals, and phalanges (Fig. 1 (a)). At each frame, the following minimization problem was solved:

$$\min_F \sum_{i=1}^{2N_c} \|F_i\|^2$$

$$s.t. \begin{cases} M(q)\ddot{q} + C(q,\dot{q}) + G(q) + \lambda + E = 0 \\ \forall i \in [1, 2N_c], F_i < F_{i,max} \end{cases}$$

With  $M(q)$  the inertia matrix,  $C(q, \dot{q})$  the centrifugal and Coriolis force vector,  $G(q)$  the gravity force vector,  $\lambda$  the generalized internal force vector,  $E$  the generalized external force vector (computed from the contact force at each contact point  $F_i$ ) and  $F_{i,max}$  the vector of maximal force available for the contact point  $i$ . Contact detection was enhanced by summing the speed of the treadmill to the center of mass velocity. Position and velocity contact detection thresholds were set at 5 cm and 0.5 m/s respectively. Data were low pass filtered at 5 Hz.

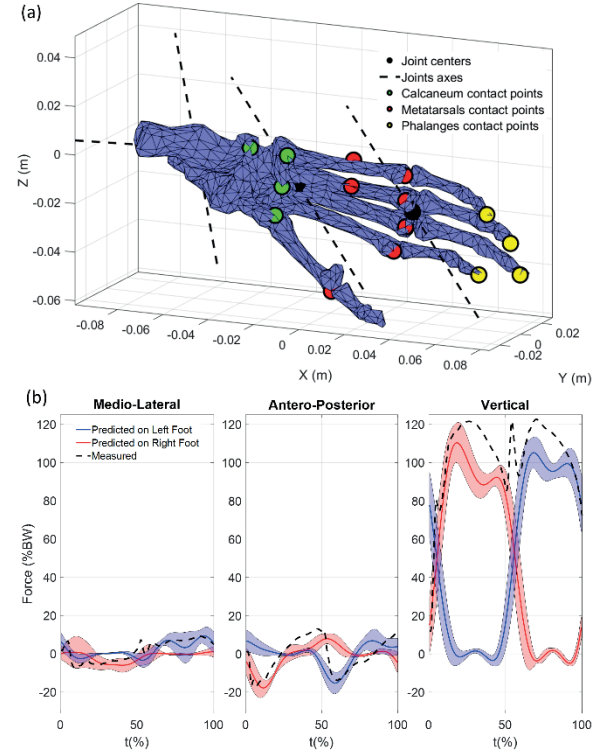
## 2.4 Data analysis

Forces below both feet were normalized by the weight of the baboon. To be compared to experimental GRF, they were resampled onto 200 frames from right foot on to left foot off.

## 3. Results and discussion

Fig. 1 (b) shows the GRF estimated for both feet. Contacts with the ground were consistent with the experimental data. Amplitudes were consistent in all directions

(vertical: 1.15 BW vs 1.20 BW, antero-posterior: 0.26 BW vs 0.30 BW, medio-lateral: 0.15 BW vs 0.17 BW), although underestimated. This may be compensated by minimizing internal forces simultaneously with GRF. Results may also be enhanced by adding more contact points and optimizing contact thresholds.



**Figure 1.** (a) Olive baboon foot. Contact points: calcaneum (green), metatarsals (red) and phalanges (yellow) & Joint axes (black) (b) Mean and standard deviation of estimated GRF on 7 different locomotion cycles, normalized by the baboon mass. Experimental GRF measured on a single platform for another baboon (black). Data are normalized by the baboon masses.

Nevertheless, the two baboons may have had different locomotion strategies leading to different patterns, although it has been shown that juvenile and adults have similar motion patterns (Druelle et al. 2022). To overcome this issue, obtaining concomitant GRF and motion capture is necessary.

## 4. Conclusions

This work is a first step towards the biomechanical study of baboon's locomotion in more natural situations. As a perspective, recent computer vision methods could

be used to estimate kinematic data of the baboon, to minimize primate equipment and perturbation.

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## Conflict of Interest Statement

None

## Contributor Roles

Conceptualization: CP, GB; Methodology: CP, GB, PMV, BR, AC, FM, FD; Software: CP, AP, FM, BW, BG; Validation: CP, GB; Formal analysis: CP, GB; Resources: GB; Data curation: GB, FD, AP, FM, AC; Writing - original draft: CP; Writing - review & editing: GB, FM, FD, AC, BR, PMV, BW; Visualization: CP; Supervision: CP, GB; Project administration: GB; Funding acquisition: GB

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Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Software, Resources, Supervision, Validation, Visualization, Writing- original draft, Writing- review & editing.

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## Data, software, code availability

<https://github.com/anmuller/CusToM>

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