

# Insights gained from a three-dimensional musculoskeletal model into ostrich pelvic limb muscle roles during walking and running gaits

Jeffery W. Rankin<sup>\*</sup>, Jonas Rubenson<sup>\*\*</sup>, John R. Hutchinson<sup>\*</sup>

<sup>\*</sup>The Royal Veterinary College, University of London, United Kingdom

*jrankin@rvc.ac.uk*

<sup>\*\*</sup>School of Sport Science, Exercise & Health, The University of Western Australia, Crawley, Australia

## 1 Introduction

Due to their cursorial evolutionary background, large body size and bipedal nature, understanding how ostrich (*Struthio camelus*) pelvic limb muscle structure is adapted to walking and running can provide new insights to help elucidate the general biomechanical principles governing movement, provide inspiration for the development of biomimetic robots and inspire the development of novel assistive devices for human movement. Recent studies have found that, despite their similar size to humans, ostriches are more cost-efficient during running and more effective at executing cutting manoeuvres when compared to human movements, likely a result of the differences in pelvic limb morphology [1-3].

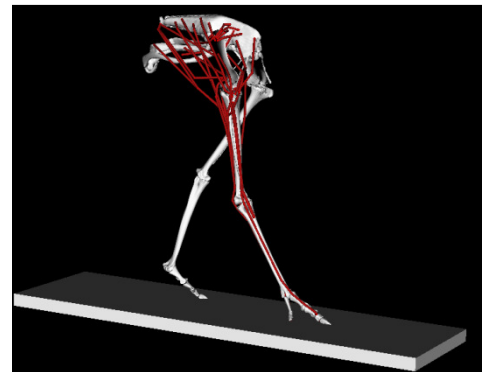
However, little is currently known about the specific roles that different pelvic limb muscles have in ostriches during walking and running, likely due to the numerous challenges in using empirical techniques (e.g., electromyography, sonomicrometry, tendon buckles) to obtain the necessary data. In addition, ostrich pelvic limb musculoskeletal structure is complex, consisting of many multi-articular muscles and a large number of joints that allow for three dimensional movement. To date, these factors have obscured how ostriches successfully meet the biomechanical demands of walking and running.

Recent advances in technology have allowed for the development of detailed musculoskeletal models that can be combined with simulation and optimisation techniques to provide muscle-specific information (e.g., musculotendon force and work) during movement. For example, human lower extremity models have been used with both static and dynamic optimisation techniques to provide new insight into the biomechanics and neuromotor control of human walking and running [4-8]. Similarly, detailed musculoskeletal models of other species have the potential to enhance our current knowledge of how animals successfully overcome the biomechanical demands of different gaits. The purpose of this study was to (1) develop the first detailed three-

dimensional musculoskeletal model of the ostrich pelvic limb based on dissection and digitization of a single specimen and (2) combine this model with a static optimisation technique to estimate pelvic limb muscle roles during walking and running.

## 2 Methods

A detailed three-dimensional musculoskeletal model of the ostrich pelvis limb was created from muscle dissection, manual digitization of muscle paths and CT scans (Fig. 1). The model consists of 70 musculotendon actuators (35 per leg) representing the major muscles of the pelvic limb. Musculotendon actuators were based on a Hill-type model that included muscle force-length-velocity relationships [9] and muscle excitation-activation dynamics were represented by a first-order differential equation with activation-deactivation constants of 10 and 15 ms, respectively.



**Figure 1:** Detailed ostrich pelvic limb musculoskeletal model. Only right side musculotendon actuators are shown for clarity.

Experimental walking (1.2 m/s; 0.64 duty factor) and running data (3.2 m/s; 0.36 duty factor) were taken from a previously collected data set [3, 10]. Three dimensional segment and joint kinematic data were calculated from high speed video (Peak Performance; Centennial, CO, USA) recordings of retro-reflective marker clusters placed on the pelvis, femur, tibiotarsus and tarsometatarsus as well as a single marker on digit III (collected at 200 Hz).

Six degree-of-freedom ground reaction forces were obtained (collected at 2000 Hz) using a force plate (Kistler, Winterthur, Switzerland). Kinetic and Kinematic data were filtered using a fourth-order, zero-lag Butterworth low pass filter (15 Hz).

To perform the static optimisations of the walking and running trials, the detailed musculoskeletal model was imported into the OpenSim [11] modelling and simulation software package. Within the package, both walking and running empirical data were combined with the model and inverse dynamics and residual reduction algorithms were used to determine joint angles that best reproduced the experimental dynamics. A static optimisation routine was then used that minimized muscle activation squared across all muscles. For both optimisations, muscle force-length-velocity relationships were retained and a time step of 0.01 seconds was used. To determine muscle roles, individual average activation levels were calculated over the stance and swing phases of both running and walking trials for each optimisation.

### 3 Results and Discussion

Overall, the stance phase had more than twice the amount of muscle activity than the swing phase during both walking and running movements, with the running tasks requiring more muscle activity in both phases (Table 1, All). With the exception of some of the hip rotator muscles (e.g., M. iliopsoas; ITCA, ITCR) and the femoral head of Tibialis cranialis (TCf), muscle actuators typically showed primary activity bursts exclusively in either the stance or swing phase (Table 1). These findings show that, similar to other birds for which electromyographic and other functional data are known [e.g., 12], ostrich muscles generally function in either a supportive/propulsive role (e.g., ankle extensors FDL and GL, Table 1) or a role in accomplishing limb progression or toe clearance (e.g., EDL, Table 1).

Relative to walking, the hip rotators (ITCA, ITCR) and distal limb muscles (FPD3, GL, FL) had large increases in overall activity during running (Table 1). ITCA mainly increased during the swing phase, with activity timing consistent with values observed in other birds [13]. All the hip rotators were also active in stance (e.g., ITCA, ITCR, Table 1), suggesting that hip rotation likely plays a critical role in both walking and running, consistent with previous inverse dynamics results that include investigations into how ostriches can perform cutting manoeuvres at high speeds [2, 3]. Ostrich distal limb muscles are highly

specialized, consisting of long elastic tendons which have a high potential to store and return energy during movement. Thus, the increased distal limb muscle activity during running found in this study suggests ostriches increase their use of these elastic structures and can help explain their comparatively high running economy [3].

**Table 1:** Average muscle activity (1 = 100% active) of select individual muscle actuators and all actuators in the model during support, swing and entire gait cycle.

| Muscle      | Stance      |             | Swing       |             | Cycle       |             |
|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
|             | Walk        | Run         | Walk        | Run         | Walk        | Run         |
| <b>FCLA</b> | 0.16        | 0.33        | 0.04        | 0.08        | 0.12        | 0.17        |
| <b>AMB1</b> | 0.64        | 0.80        | 0.28        | 0.11        | 0.51        | 0.36        |
| <b>ITCA</b> | 0.12        | 0.23        | 0.03        | 0.33        | 0.09        | 0.29        |
| <b>ITCR</b> | 0.78        | 0.52        | 0.14        | 0.48        | 0.56        | 0.50        |
| <b>FMTL</b> | 0.79        | 0.78        | 0.17        | 0.18        | 0.57        | 0.40        |
| <b>TCf</b>  | 0.23        | 0.63        | 0.30        | 0.38        | 0.26        | 0.47        |
| <b>FDL</b>  | 0.90        | 0.68        | 0.02        | 0.02        | 0.59        | 0.26        |
| <b>FL</b>   | 0.30        | 0.45        | 0.02        | 0.08        | 0.20        | 0.22        |
| <b>FPD3</b> | 0.06        | 0.32        | 0.02        | 0.02        | 0.04        | 0.13        |
| <b>GL</b>   | 0.06        | 0.23        | 0.02        | 0.05        | 0.04        | 0.12        |
| <b>EDL</b>  | 0.03        | 0.08        | 0.17        | 0.28        | 0.08        | 0.21        |
| <b>All</b>  | <b>0.22</b> | <b>0.31</b> | <b>0.08</b> | <b>0.13</b> | <b>0.17</b> | <b>0.20</b> |

While a major advantage of the static optimisation technique used in this study is its low computational cost, the optimisation method is time-independent and has been criticized as lacking a physiological rationale. However, muscle force predictions between static and dynamic approaches have been found to be similar in human walking [14]. Future work is necessary to determine if these results extend to other movements, such as running, or different morphologies, such as in ostriches. Regardless, a detailed three-dimensional musculoskeletal model such as the one developed in this study has great potential to generate new insights into ostrich gait mechanics that can help elucidate general principles of bipedal walking mechanics and inspire new biomimetic devices.

### 4 Open Questions

Detailed musculoskeletal models and optimisation techniques have great potential to improve our understanding of the biomechanical principles underlying movement. However, like all models they have limitations and questions to guide model development such as “How can we improve a model’s ability to represent the true

system (e.g., better represent muscle architecture)?" or "How can we improve our ability to validate models when experimental data are limited?" must be better addressed—to advance the current state-of-the-art. In addition, the nature of detailed musculoskeletal models makes them well suited to theoretical studies (e.g., What happens if muscle force generation capacity is reduced?). More discussion related to exploring how musculoskeletal models and simulations can be used to inform biomimetic robotic development should increase interdisciplinary ties between biology and robotics.

### 5 Acknowledgements

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