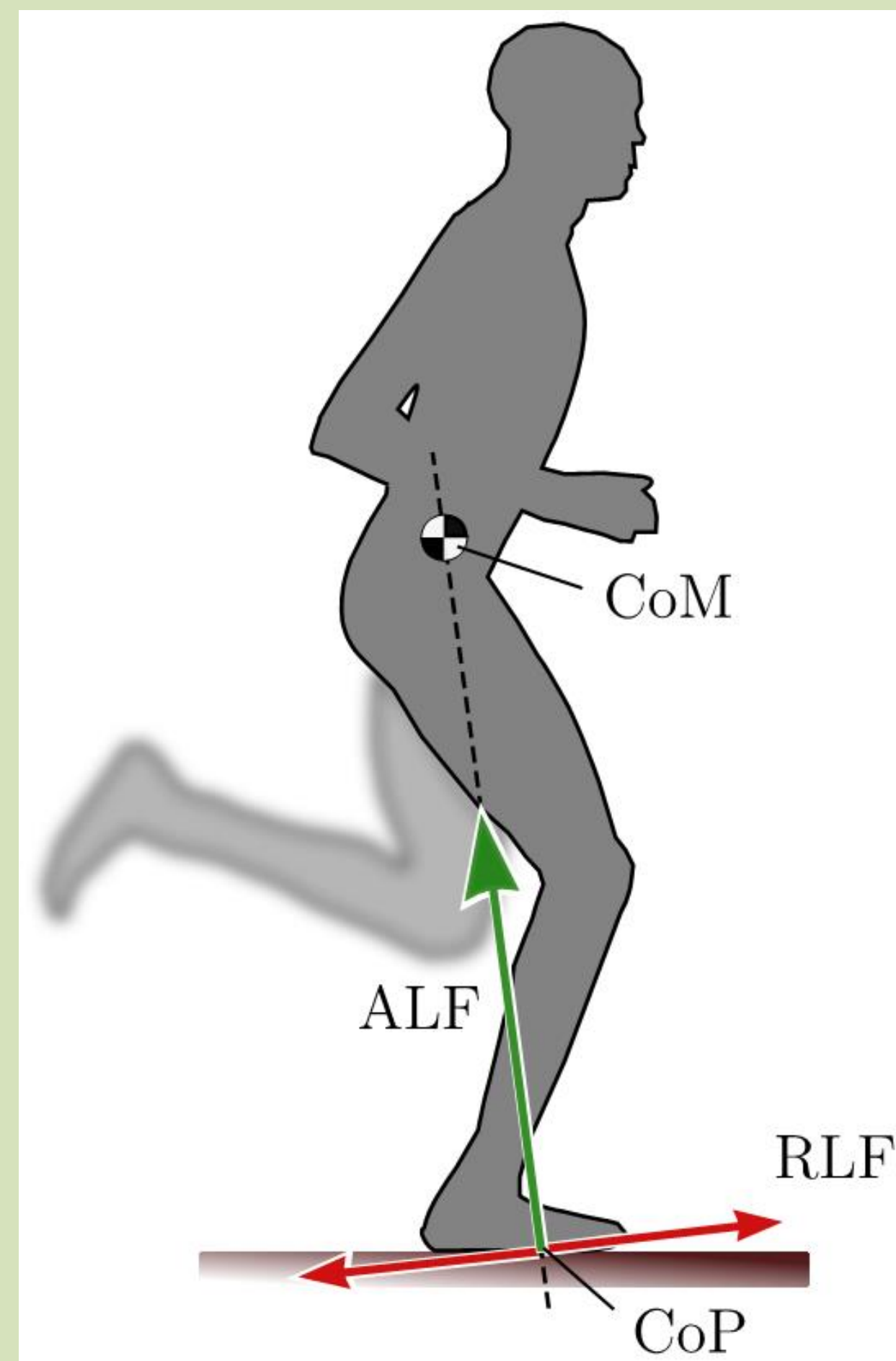


## Introduction

Balance is key to human stance but equally required for many other movements. Balance may rely on control of ground reaction force (GRF) direction and its center of pressure (CoP).

During walking and running, the leg function can be described by a prismatic leg spring. This axial leg function (ALF), must be complemented by an orthogonal rotational leg function (RLF) to achieve additional goals, e.g. postural control, leg retraction, and swing leg alignment.



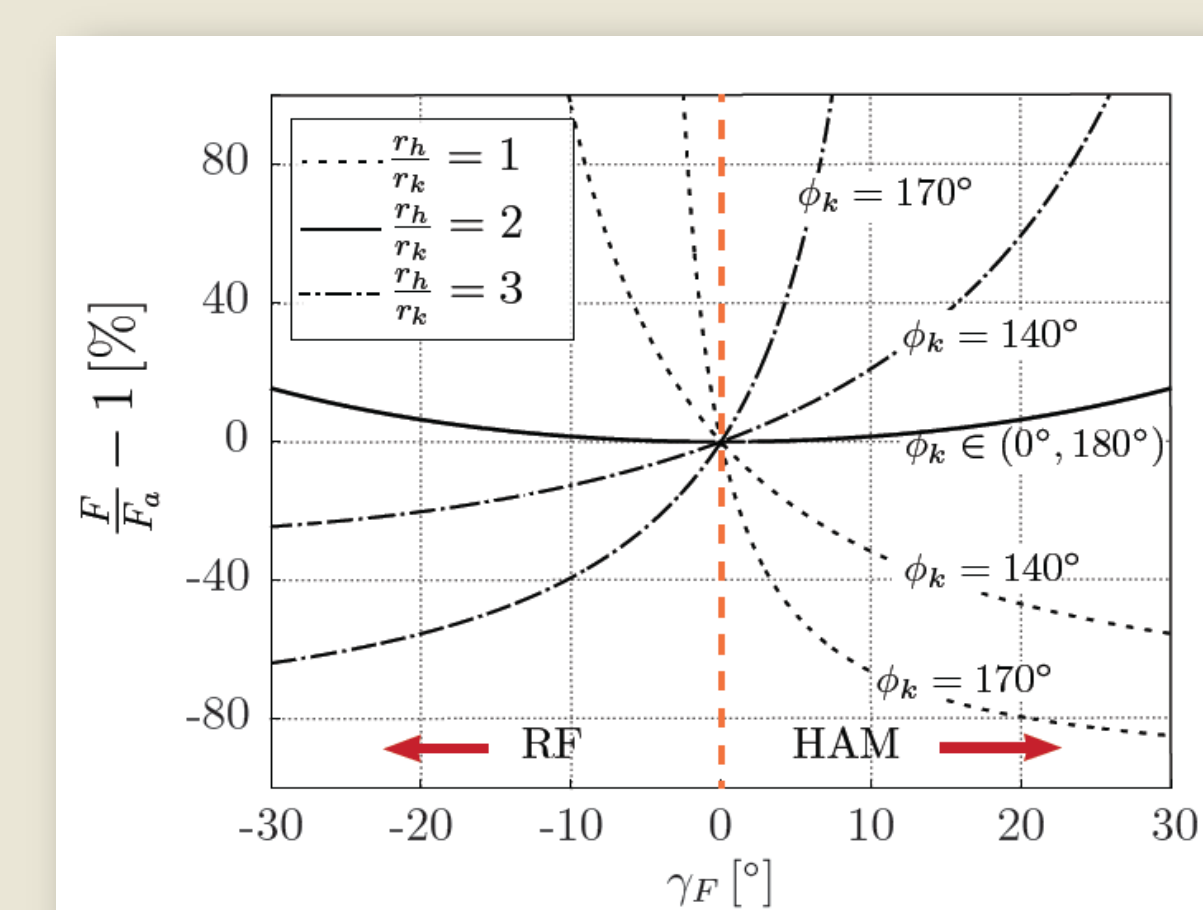
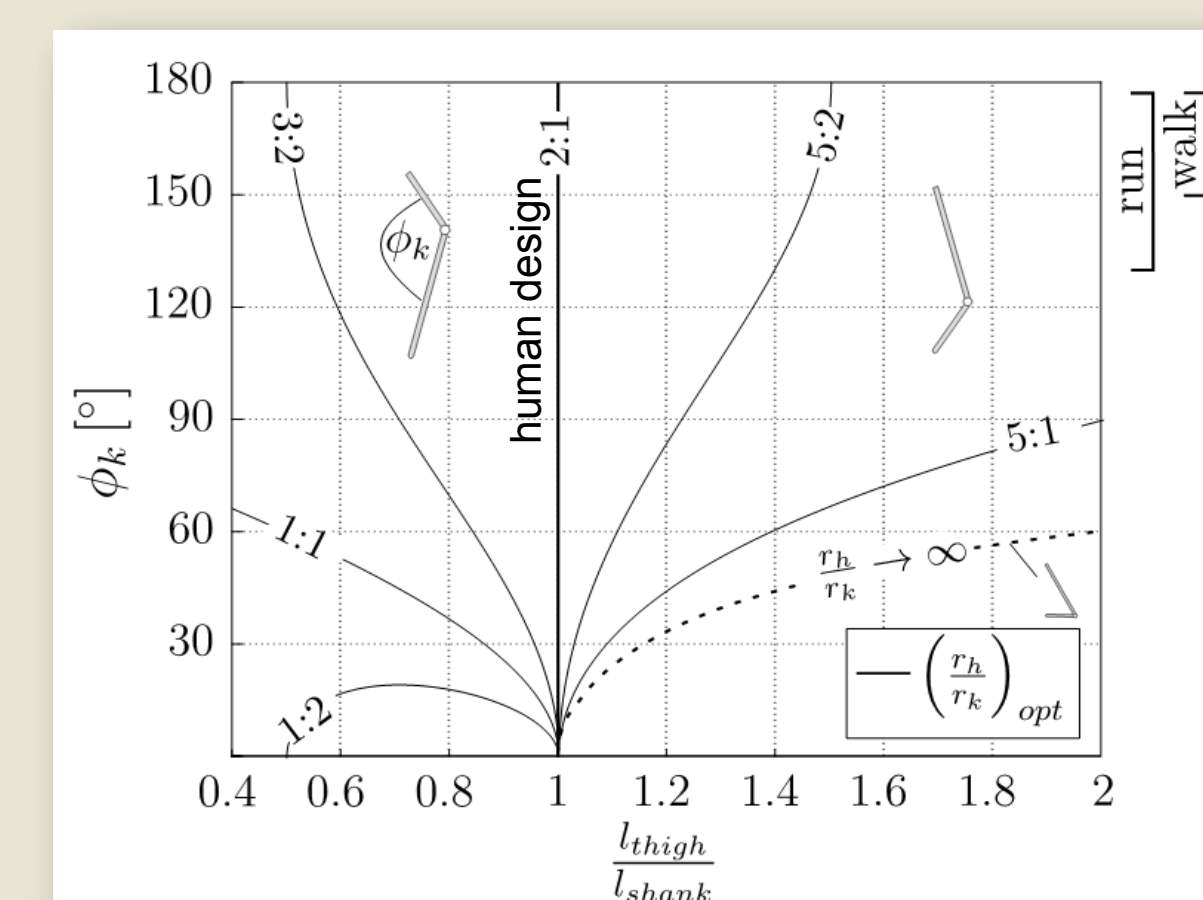
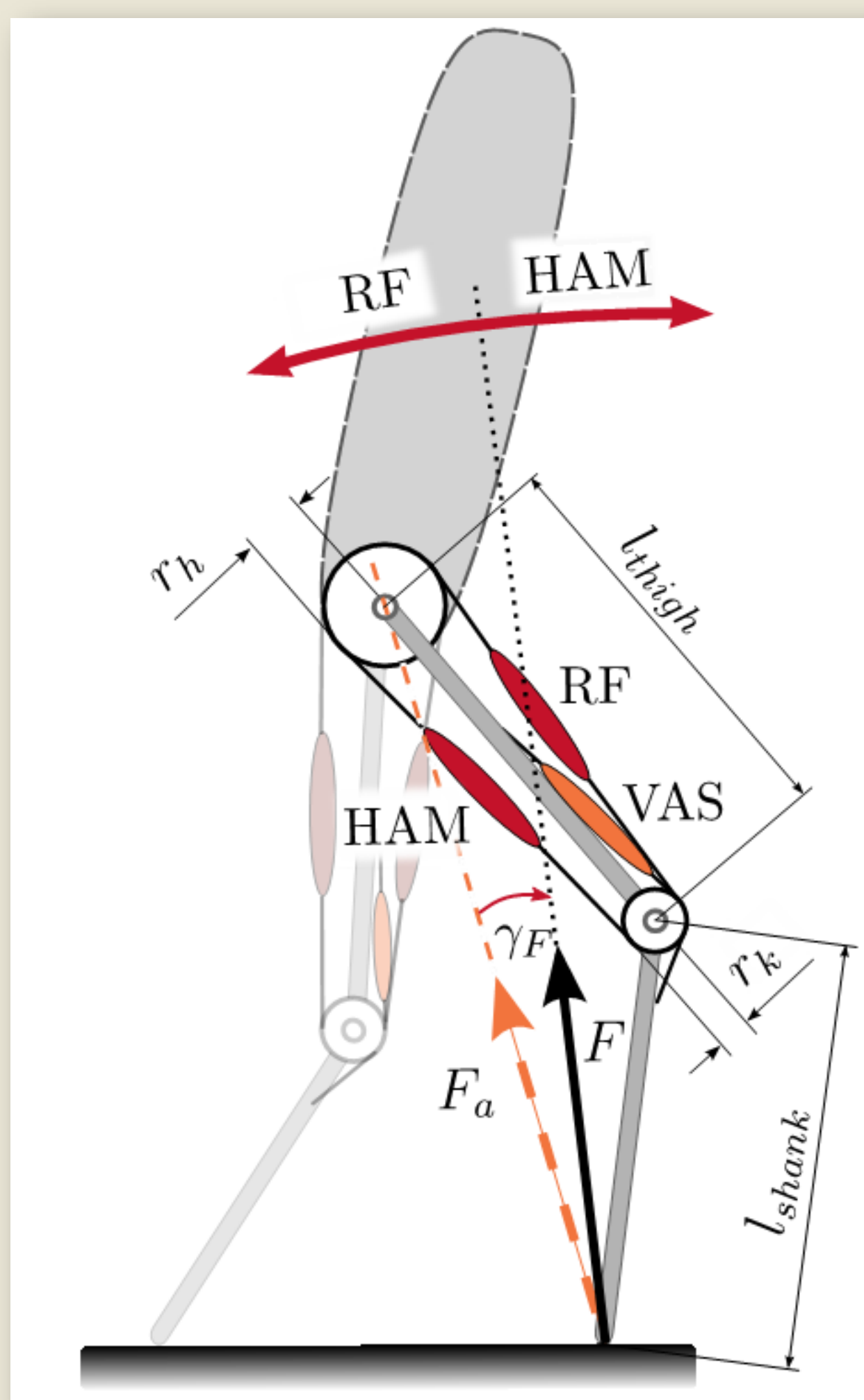
It is not clear how these functions may be realized efficiently in the segmented human leg. Here we investigate how the structure of the musculoskeletal system might provide access to the RLF independent of the ALF.

**Fig. 1.** The ground reaction force (GRF) can be decomposed in perpendicular components (green and red arrows) associated with axial (ALF) and rotational leg function (RLF), respectively. Here, the leg axis is defined by the center of mass (CoM) and the center of pressure (CoP).

## Static analysis

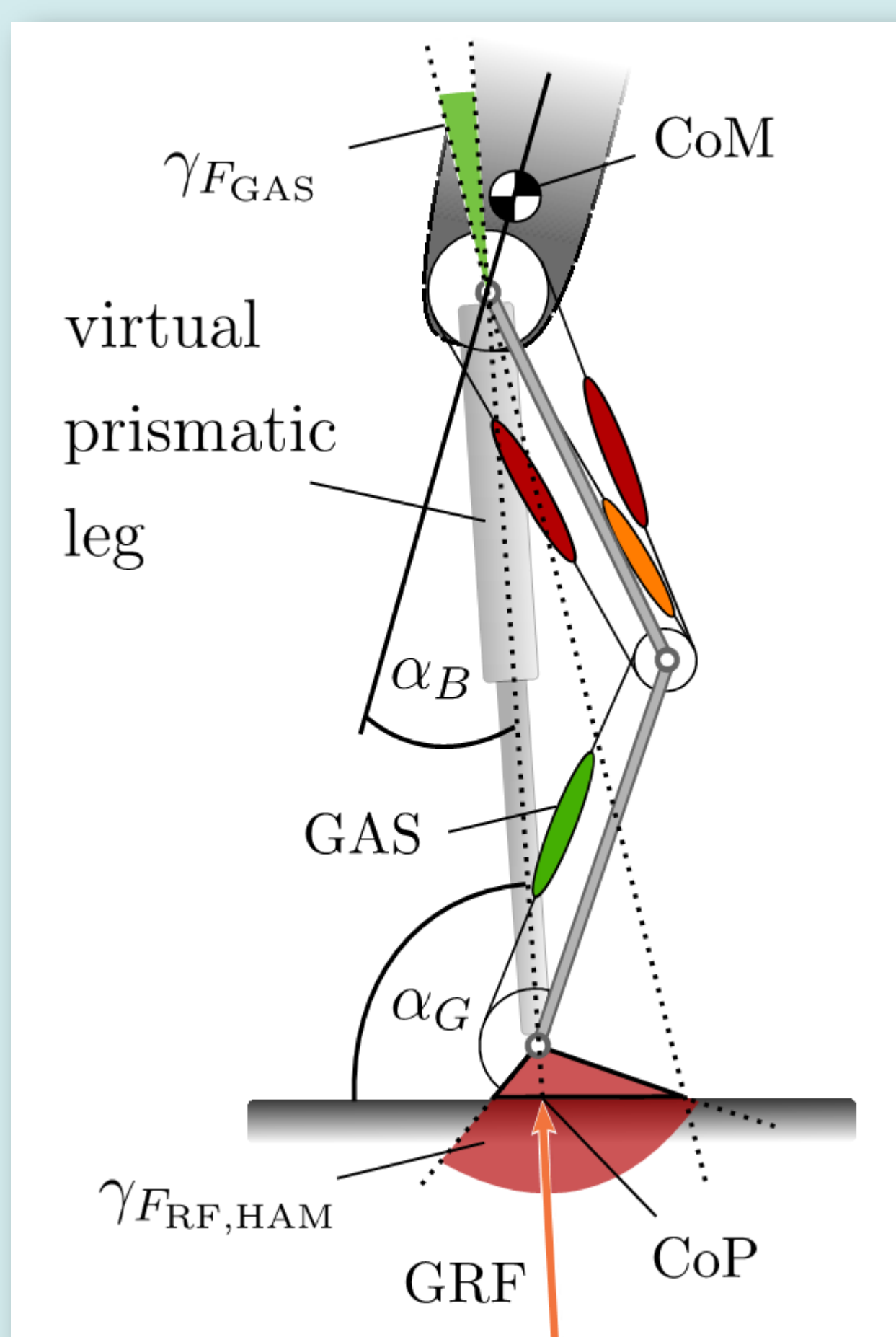
Separate access to RLF – independent of ALF – is provided by the action of two-joint muscles for 1:1 thigh to shank and 2:1 biarticular hip to knee muscle moment arm ratio. With this morphology, the model is accessible like SLIP models with prismatic leg and hip torques.

**Fig. 2.** Steering ground reaction force (GRF) direction  $\gamma_F$  with biarticular thigh muscles. Ideally, biarticular muscles (rectus femoris RF, hamstrings HAM) introduce a force component perpendicular to the axial force  $F_a$ , here introduced by monoarticular vastii (VAS).



In contrast to HAM and RF, biarticular gastrocnemius (GAS) rotates GRF about the hip and mainly controls the CoP. HAM and RF control the amount of torque applied on the body. Altogether, biarticular muscles unify actuator and sensor function with respect to RLF.

**Fig. 3.** All biarticular muscles have the same sensitivity on  $\gamma_F$ . RF and GAS rotate GRF clockwise. Biarticular muscles measure virtual prismatic leg axis orientation with respect to ground ( $\alpha_G$ ; GAS) and with respect to the body ( $\alpha_B$ ; RF, HAM). Their lengths remain constant (0) for increasing leg length, and increase (+) or decrease (-) with either  $\alpha_G$  or  $\alpha_B$ .



muscle forces influence leg kinetics

| sensitivity chart |       |       |            |     |                |
|-------------------|-------|-------|------------|-----|----------------|
|                   | $F_a$ | $F_p$ | $\gamma_F$ | CoP | torque on body |
| HAM               | ○     | ●     | ●          | ○   | ●              |
| RF                | ○     | ●     | ●          | ○   | ●              |
| GAS               | ○     | ●     | ●          | ●   | ○              |
| VAS               | ●     | ○     | ○          | ○   | ○              |

muscle lengths sense leg kinematics

| dependency chart |                  |                   |                   |  |
|------------------|------------------|-------------------|-------------------|--|
|                  | $\Delta L_{Leg}$ | $\Delta \alpha_B$ | $\Delta \alpha_G$ |  |
| $\Delta l_{VAS}$ | -                | 0                 | 0                 |  |
| $\Delta l_{RF}$  | 0                | -                 | 0                 |  |
| $\Delta l_{HAM}$ | 0                | +                 | 0                 |  |
| $\Delta l_{GAS}$ | 0                | 0                 | +                 |  |

## Conclusion

As the predicted ratios are approximated in nature, balance control can be simplified by the architecture of the human leg. The high-dimensional segmented body can be accessed like a simple virtual model

but can still be exploited with all its functional degrees of freedom. This concept opens up new perspectives for understanding postural control. Future studies must show how this concept relates to alternative approaches, for example postural control by monoarticular muscles.

### Acknowledgement

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