

# Walking stabilized by body mechanics and heel-to-toe center-of-pressure shift provides insight on control of upright posture

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DP

## Behavior:

### Control of Whole-body Angular Momentum

- Bipedes must average zero whole-body angular momentum (WBAM) for steady state walking
- Force of the ground on the foot ( $F$ ) is the only force that can change WBAM
- $F$  must be controlled
- $F$  results from the neural activation of muscles coupled with the governing system mechanics
- The neural control has latitude in its ability to set location and direction of  $F$

What neural control strategy do humans use to control  $F$  and thus, WBAM?

### Observation from Walking

- WBAM varies systematically through the gait cycle (Fig. 4)
- $F$  is well-described as having vector lines-of-action through the cycle that pass near a common point (called a divergent point, or DP) in a body-fixed reference frame<sup>1</sup> (Fig. 1)
- The DP is located above the CM (Fig. 1)
- The DP describes a systematic relationship between location of application of  $F$  relative to the CM (center of pressure, or CP) and the direction of  $F$

The neural and mechanical contributions to the DP must be uncoupled to understand the underlying control

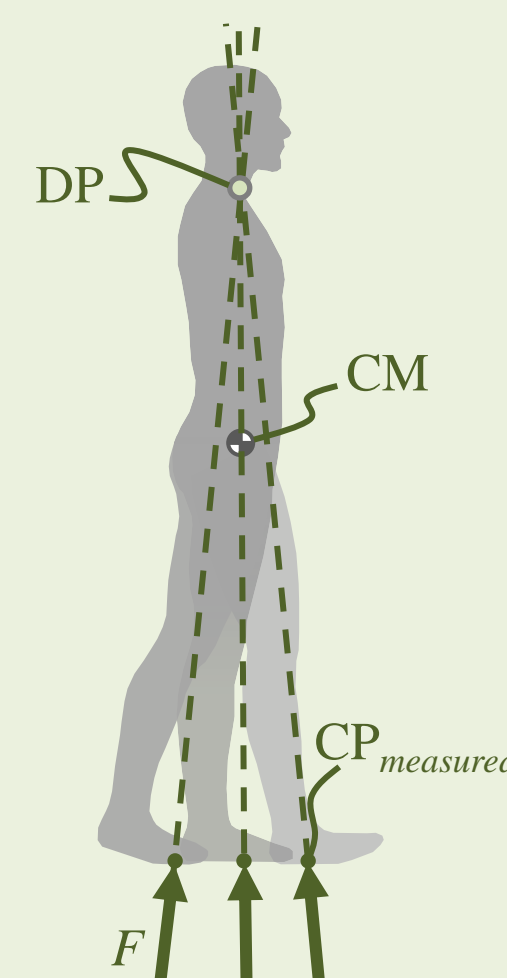


Fig. 1 DP

### Stability Benefits

- The location of the DP above the CM indicates that  $F$  has an appropriate direction so that torque about the CM can be made larger by increasing  $|F|$  to accelerate the body toward upright (Fig. 4)
- Humans have the ability and preference to preserve  $F$  direction while increasing  $|F|$ <sup>4</sup>
- DP behavior embeds perturbation resistance without the need for additional control

Understanding the  $F$  pattern of human upright walking provides insight on producing stable walking in any bipedal mechanism

## Upright Walking

### Organization of Control

- Stable walking in any biped requires control of a mechanical system behaviorally governed by physics
- Humans accomplish control of upright posture by implementing neurological control that interacts with the physically imposed mechanics such that WBAM oscillates systematically while averaging zero<sup>1</sup> (Fig. 4)
- The corresponding  $F$  behavior that causes oscillation in WBAM is characterized by a DP, a systematic relation between  $F$  location of application and  $F$  direction (Fig. 5)
- $\Pi$  describes the mechanical contribution of heel to toe CP shift, so this attribute of walking was decoupled from DP behavior by fixing CP under the foot to observe the remaining  $F^{2,3}$  ( $\xi$ , Fig. 5)
- The remaining  $F$  behavior can be summarized as being directed from the ball of the foot through the CM, a default control useful for bipedal tasks requiring zero change in WBAM (Fig. 5)
- Exploitation of  $\Pi$  mechanics by walking heel to toe primes the system to provide corrective torque about the CM

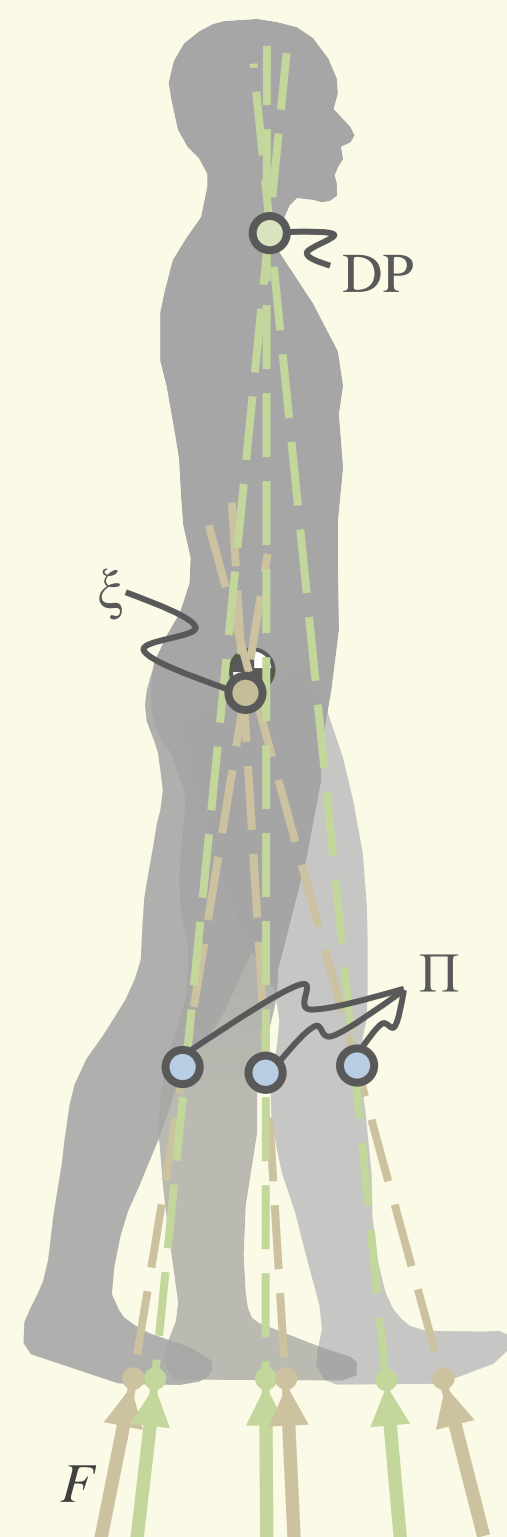


Fig. 5  $\xi + \Pi = DP$

## control &

### Uncoupling the Effect of CP Shift Relative to the Foot

- The mechanical effect of ankle torque modulation on CP and  $F$  direction (see description of  $\Pi$  mechanics below) was removed from human walking data using a seven-segment rigid body linkage model
- The CP was fixed with respect to the foot through stance by applying the necessary ankle torque
- The resultant  $F$ 's across the cycle were calculated
- Those  $F$  vector lines-of-action through the cycle were well-characterized as passing near a common point<sup>3</sup> ( $\xi$ , Fig 2)

$\xi$  describes the motor control output decoupled from the mechanical effect of heel to toe walking

### Proximity of $\xi$ to the CM

- This study characterized the  $F$  that would be produced in a walking human in the absence of heel to toe CP excursion
- With the CP fixed to the ball of the foot, those  $F$  vectors yield a  $\xi$  nearly coincident with the CM<sup>3</sup>
- A control strategy that directs  $F$  through the CM cannot produce torque to accelerate the body towards upright

Without the modulation in ankle torque that causes heel to toe walking, feedback mediated muscle action to restore upright posture would be necessary

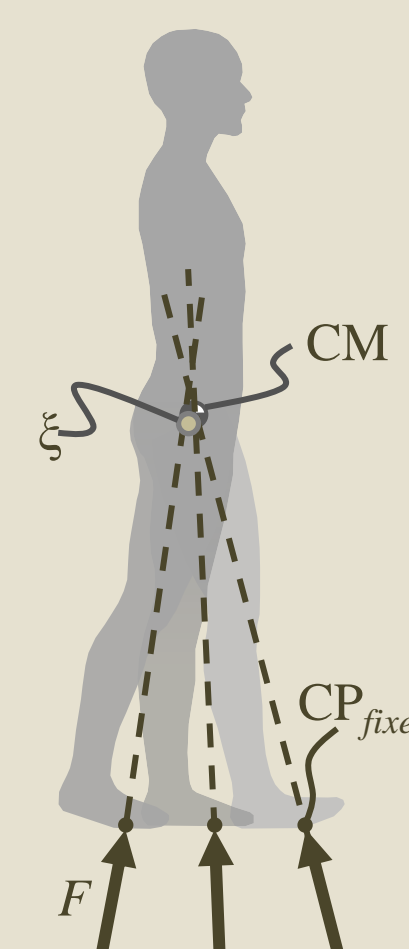


Fig. 2  $\xi$

### Implications for Stability and Other Bipedal Tasks

- Nearly all of the stability gained from a DP located above the CM can be attributed to the exploitation of linkage mechanics (characterized by  $\Pi$ ) and heel to toe CP shift
- CM-centric control is favorable for a sudden increase in  $|F|$  required to jump
- In populations that walk with restricted CP excursion (e.g. stroke and cerebral palsy), active compensation may be required to offset a stability deficit

Control organized with a CM-centric  $F$  direction component coupled with ankle torque is favorably tuned to regulate WBAM during both walking and performing other bipedal tasks

$\Pi$

## mechanics

### Modeling to Characterize Mechanics

- Body modeled as seven-segment rigid-body linkage with non-accelerating stance foot
- Segment inertial parameters, velocities, and joint torques from human walking data applied to model at instantaneous postures in stance
- Study of neural control indicates control of ankle torque independent of hip and knee torques<sup>5,6</sup>
- At instantaneous postures, ankle torque alone was modulated to shift CP relative to the foot
- The effect on  $F$  direction was observed (Fig. 3)

At a single posture and state,  $F$  is constrained to pivot about a point,  $\Pi$ , with change in ankle torque<sup>2</sup>

### Mechanical Contribution to $F$ of Heel to Toe CP Shift

- Change in ankle torque systematically alters torque about the CM by changing the CP and the direction of  $F$
- The excursion of the CP with respect to the foot is typically heel (early stance) to toe (late stance)
- The presence of a preference for heel to toe walking and  $\Pi$  mechanics means that these contribute to the systematic pattern of  $F$  observed in walking (Fig. 1)

$\Pi$  describes a mechanical component that can be removed from walking behavior to help characterize remaining control

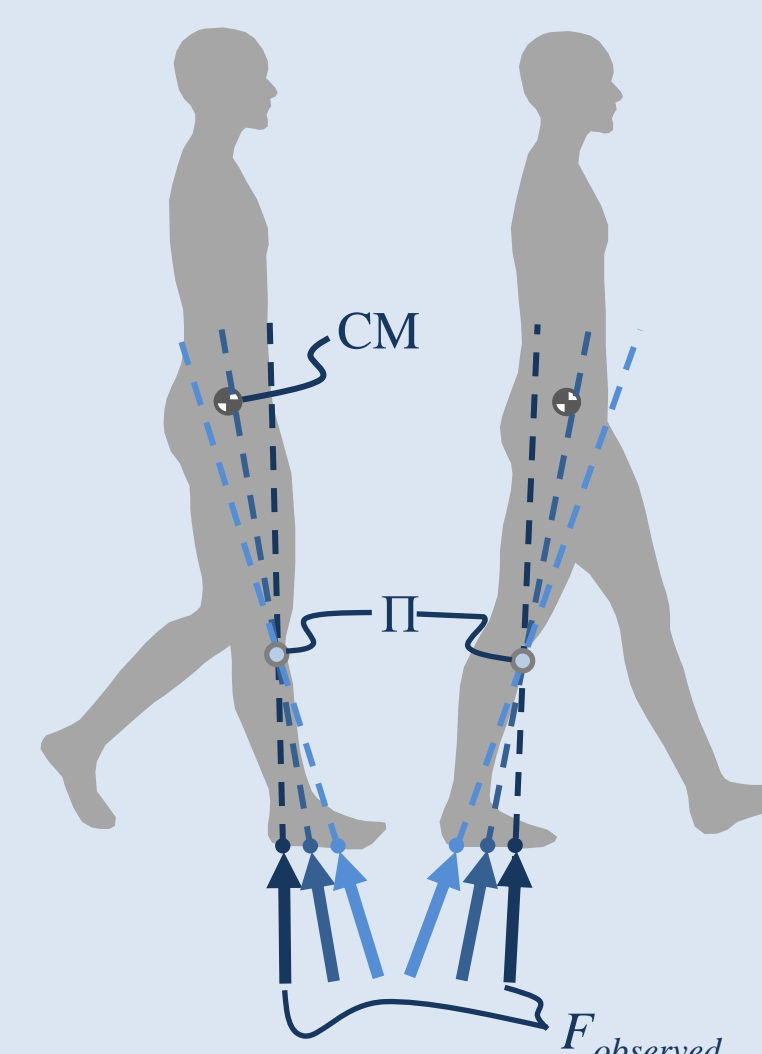


Fig. 3  $\Pi$

### Stability Contribution of Heel to Toe Walking

- The mechanical effect of  $\Pi$  combined with typical heel to toe CP excursion results in a more stabilizing  $F$  through stance
- The locations of the  $F$  vectors consistent with heel to toe walking ( $F_{observed}$ , Fig 3) have stabilizing moment arms ( $r$ ) about the CM
- $F_{observed}$  (Fig 3) provides greater angular acceleration in the direction needed to move the body toward upright for each phase of the cycle (Fig 4), stabilizing upright body posture

Change in CP via ankle torque modulation can be exploited in bipedal control to produce torque that accelerates the body towards upright

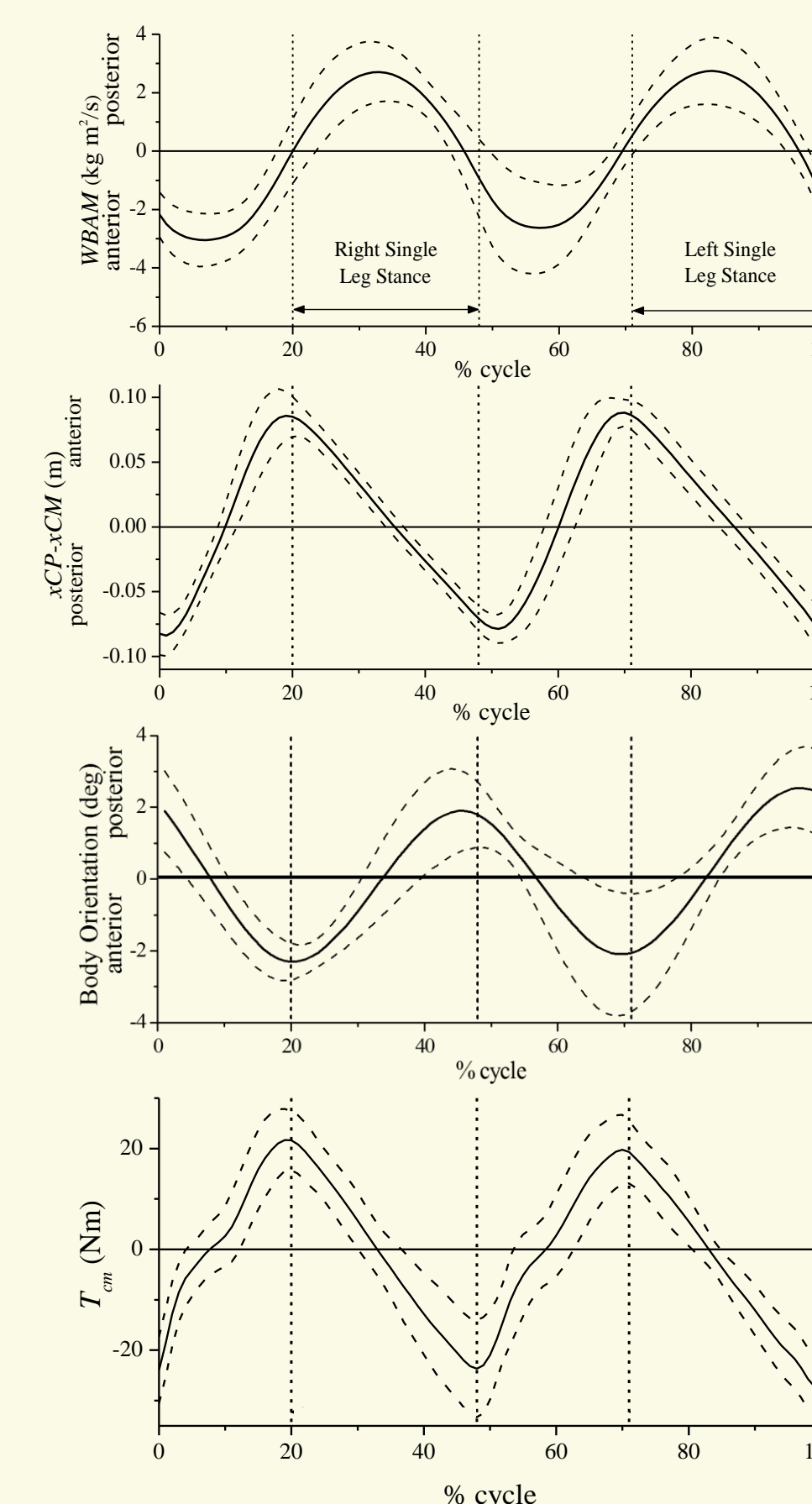


Fig. 4 Walking data

Understanding the organization of walking in humans from this novel perspective provides an approach for building effective bio-inspired robotic systems

### Additional Implications

- Development of robotic orthoses and prostheses to restore impaired walking
- Novel treatments for individuals suffering from walking impairments due to stroke, cerebral palsy, etc.
- Design of fall prevention therapies for humans

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