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

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1 Introduction

In the field of robotics, bipedal control strategies that aim to replicate human behavior do not completely capture the many attributes of human walking. This is understandable given the inadequate understanding of how complex neural and mechanical mechanisms produce the human behavior those robots target to replicate. To advance the field, it is important to maintain a perspective of how similar the objective is between robotic design and the study of human walking; both fields aim to determine the control strategy of a mechanical system behaviorally governed by physics, albeit the origin of that control is carefully calculated in robotics and unconsciously neurological in humans. Breakthroughs toward the shared goal of understanding how to maintain the upright posture characteristic of human walking lie in the convergence of the theories and characteristics associated with each field. This interdisciplinary approach is exemplified in our current body of work.

Here, a fresh perspective on neural control of human walking is provided that may also be applicable to development of robotic control strategies. A focus on characterizing the force of the ground on the foot (F) is used, as this is the only variable that can change the critical quantity of angular motion that needs to be controlled to retain upright posture during walking. The neural control of human walking is approached by observing (F) during intact human gait and separating out a well-characterized behavior of the mechanical linkage. We focus on that mechanical behavior and present a general discussion of how it generates stability during human walking.

The F vectors typical of human gait are well-described as having lines-of-action that pass near a common point through the gait cycle, resulting in a pattern of angular momentum oscillating around zero [1,2]. That point is located above the center-of-mass and is called the divergent point (DP) (Fig. 1). While many common models of walking and robotic control strategies are rooted in a theoretical goal of constant zero angular momentum, inevitable perturbations and terrain irregularities necessitate meticulous feedback control to meet such a goal. It is important not to overlook the potential utility of allowing systematic deviation in angular momentum as observed in human walking. A set of F vectors described by a DP is advantageous in that it provides torque about the center-of-mass (CM) that accelerates a rigid body back toward upright from any posture. Control of F to replicate DP behavior may be a valuable strategy to consider in design of robots, in that it stabilizes posture without additional control.

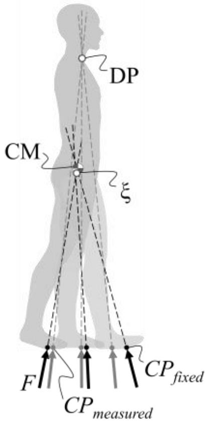

Figure 1. Typical F vectors observed in walking ($CP_{measured}$) pass near a divergent point (DP) above the CM. With only change in T_A to fix the center of pressure with respect to the foot (CP_{fixed}), those F vectors pass near the CM (ξ).

Implementation of such a control strategy requires further delineation of the mechanical and neurological components that result in DP behavior in humans. This study focuses on characterizing the mechanical contribution of center-of-pressure shift relative to the foot ($x'CP$, typically heel to toe) to overall walking behavior and then examines the F that remains when that contribution is removed. Evidence of human's ability to modulate ankle torque (T_A) independently of hip and knee torques [3,4] motivated T_A modulation as a realistic means of shifting $x'CP$ to study its contribution to the F observed in walking.

2 Methods

Analysis of the single-support stance-phase F vectors used a seven-segment rigid-body linkage model of the human articulated to move only in the sagittal plane. Human walking data was used to set body postures, velocities, and joint torques. Assuming a non-accelerating stance-foot, the linearity of the equations of motion indicate that for any instantaneous posture in stance, modulation of T_A alone will pivot the *F* vector about a point near the knee (Π, Fig. 2) [5]. Therefore, change in both the direction and location of *F* relative to the CM (and thus, torque about the CM) is mechanically constrained with modulation of T_A.

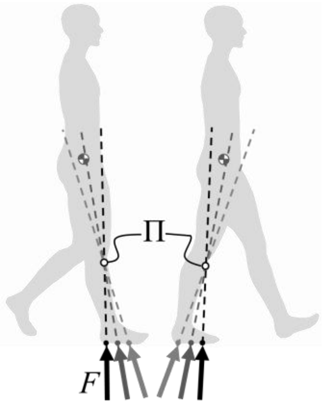

Figure 2. The force of the ground on the foot (*F*) is mechanically constrained to intersect a point near the knee (Π) with T_A modulation. Force vectors typical of human walking shown in black for early (left) and late (right) stance provide the greatest righting torque.

These Π mechanics are inherently present in the system, so when humans typically walk heel to toe, part of the systematic change in *F* can be attributed to them. To capture that contribution, heel to toe *x′CP* was removed from walking data by modulating T_A through the cycle to fix *x′CP*. The resulting *F* characterized the hip and knee torque component of the motor control used to walk.

3 Results

In the absence of *x′CP* shift, the *F* vectors through stance are well described as passing near a common point (ξ, Fig. 1). That point was located near the CM, particularly with *x′CP* fixed at the ball of the foot.

4 Discussion

This study characterizes the *F* and thus, torque about the CM that would be present in a walking human in the absence of the T_A control that shifts *x′CP*. It shows that the DP behavior observed in walking is the result of neural control of hip and knee torques (that alone would result in *F* passing near the CM) coupled with T_A modulation. That T_A control mechanically redirects *F* to pass near a point *above* the CM, an inherently stable strategy that produces an increased righting torque for increased body tilt.

The hip and knee torque thus characterized only produce a force directed through CM, which cannot cause any angular acceleration to affect upright posture. This control alone would not be sufficient to maintain upright posture without additional feedback control to attenuate perturbations and controller error. Rather than rely solely on additional active control resources, humans appear to embed a passive stabilizing mechanism by walking heel to toe. This *x′CP* excursion exploits the mechanical effect described by Π to cause nearly all of the stabilizing torque characterized by the DP throughout stance (Fig. 2).

A level of control that directs *F* through the CM with *x′CP* at the ball of the foot is useful, however, for additional tasks that require upright posture such as a sudden increase in *F* magnitude used to jump. Take-off from the ball of the foot maximizes ground contact time, and with the ξ pattern of *F* control does not cause unwanted angular acceleration.

The many benefits of this motor control organization described in humans may provide insight on novel control strategies for robotic bipeds. Reproducing the stable DP behavior in robotics may be accomplished by layering similarly organized control. This modular understanding of human control may also provide insight on more useful approaches for development of robotic orthoses and prostheses to restore impaired walking.

5 Open questions

1. How can design of robotic control benefit from the divergent point, Π mechanics, and ξ descriptions of human walking that are presented here? What conditions are required?

2. What features of the system give rise to the divergent point, Π mechanics, and ξ?

3. What role do joint torques and stiffness play in this description of the system?

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