



Robotic Walking in the Real World

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mom-5, and *Dishevelled/dsh-2/mig-5*—lead to defects in mitotic spindle orientation and cell fate specification of blastomere and other cell types (11). Normally in these cells, the homolog of the transcription factor that binds to β -catenin, *TCF/pop-1*, is asymmetrically enriched in one daughter cell. However, mutations in *TCF/pop-1* itself disrupt cell fate determination but have no effect on orientation of the mitotic spindle, indicating that Wnts act through a transcription-independent mechanism for initial cell polarization (11). Habib *et al.* did not assess TCF-family members in mouse ES cells nor perform loss-of-function studies for β -catenin or TCF. Thus, it is unknown whether there is a transcriptional requirement for the ability of Wnt3A to polarize ES cells. There are notable differences in the biochemical details between the vertebrate Wnt- β -catenin pathway and the *C. elegans* Wnt asymmetry pathway (12). It remains to be determined whether any aspects of this signaling are evolutionarily conserved.

Another possible mechanism of Wnt-dependent asymmetry involves the interaction between the canonical Wnt- β -catenin signaling pathway and the Wnt-planar cell polarity (Wnt-PCP) signaling pathway,

which can polarize cells (13). Wnts that affect Wnt-PCP signaling, such as Wnt5A, can antagonize Wnt- β -catenin signaling (14). Habib *et al.* found no effect of Wnt5A beads alone; however, when dividing ES cells were bathed in Wnt5A, the ability of Wnt3A beads to promote asymmetry was inhibited. As cells *in vivo* are often exposed to multiple different Wnts, it will be informative to characterize the behavior of ES cells exposed to multiple beads with different Wnts acting through the Wnt-PCP and Wnt- β -catenin pathways. Alternatively, recapitulating Wnt3A-mediated asymmetry with microfluidic gradients (15) would make it possible to examine cell behavior in antiparallel or orthogonal concentration gradients of Wnts with opposing activities.

The study of Habib *et al.* is a modern response to questions posed by developmental biologists since the late 1800s and early 1900s regarding spatial asymmetries in informational molecules. Even after 30 years of study, molecular details of Wnt signaling are still being uncovered. Indeed, on page 1436 of this issue, Cruciat *et al.* (16) identify an RNA helicase (DDX) as part of the Wnt pathway, and on page 1441, Huang *et al.* (17) report that an enzyme (receptor

interacting protein kinase 4) interacts with a Wnt receptor to control signaling. As our understanding of Wnt signaling keeps expanding, and experimental approaches to dissect the details improve, manipulating the Wnt pathway as an effective treatment for disease may become a greater possibility.

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APPLIED PHYSICS

Robotic Walking in the Real World

Melany L. Hunt

Movement of robots over rough or unstable terrain is an outstanding challenge, especially for tasks such as remote planetary exploration, but animals manage such locomotion tasks every day. For example, in a natural environment, a lizard can traverse a sandy or pebbled surface in such a way that its limbs can push and move individual grains, which allow its limbs to penetrate beneath the surface of the loose layer. On page 1408 of this issue, Li *et al.* (1) present experiments and modeling of a biologically inspired, six-legged robotic device that was designed to move efficiently across a bed of dry, loose granular material. Based on the mechanics data, simulations were developed to identify designs that maximized walking speed.

The authors quantified the effect of the

limb intrusion by measuring the lift and drag forces on a simulated leg (a small rigid plate) as it entered and was extracted from loose surfaces at different orientations to the granular surface. In the current experiments, flat beds of glass beads or poppy seeds were used. These measured forces were used to model the stresses, given the assumption that the stress was linearly dependent on depth within the layer and independent of the speed of intrusion.

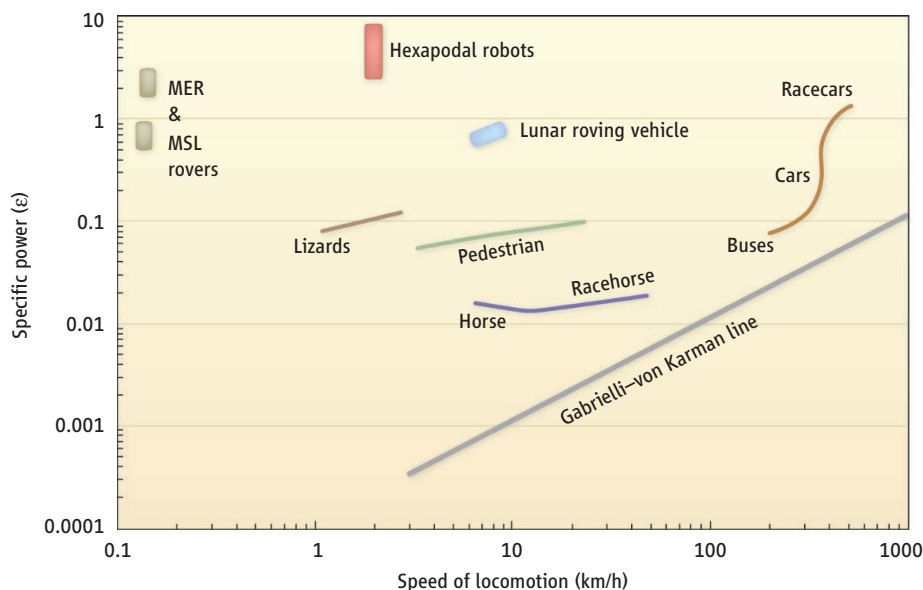
The authors then used the stress relations to compute the forces, the overall movement, and the forward speed versus time of their robot. These simulations were then compared with experimental measurements for a range of stride frequencies and differing leg shapes. From their simulation methodology, the authors note that the design of the robotic legs can be optimized for speed—in this case, a maximum speed of 72 cm/s for a forward C-shaped leg at a stride frequency of 5 Hz.

Studies of the mechanical stresses on plates moving through loose materials were used to simulate and optimize robot locomotion over soft ground.

This field of research is often described as terramechanics, the study of vehicle performance relative to its terrain (1–3). Terramechanics includes the locomotion of small robots (1, 4) and lizards (5), as well as the transport of off-road vehicles (2, 3), tractors, military tanks, the Lunar Roving Vehicle (LRV) used in Apollo missions in the early 1970s (6), and martian rovers, including the Mars Exploration Rovers (MER) launched in 2003 (7) and the Mars Science Laboratory (MSL) that landed in August 2012 (8). The work by Li *et al.* used the term “terradyamics” to emphasize the potential movement of the deformable terrain.

In terramechanics or terradyamics, the vehicle locomotion depends critically on the transmission of forces between the deformable terrain and the wheels, tracks, or legs of the vehicle. As illustrated by Li *et al.*, the mathematical relations for the forces are often unknown and depend on the local state of the granular material, the properties of the

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grains, and the deformation rate (or speed of the intrusion) of the material. This study and others have demonstrated that the vehicle performance in terms of energy efficiency and speed depends critically on the terrain properties (2–4, 9). The terrain conditions may also prohibit vehicle motion, as was the case with the MER rover Spirit that ended its 6-year, 7.7-km journey across a rich variety of martian topography when it breached a thin surface crust and became embedded in underlying loose soil (10).

Early developments in terramechanics are often credited to the work by Bekker (2). His 1960 text on off-road locomotion began with a figure showing the vehicle power per weight as a function of locomotion speed. Similar information based on the dimensionless specific power, ϵ , is shown in the figure. As was done in the original figure by Bekker, the figure here includes the Gabrielli–von Karman line, which was first presented in 1950 as an empirical fit of the best performance (lowest ϵ) for a range of vehicles (air, water, and ground) and speeds (10). Unlike the original Gabrielli–von Karman plot, Bekker’s figure included animals and off-road vehicles to emphasize that vehicles and creatures traversing sands and soils have lower performance than when operating on hard, flat surfaces.

The figure includes data for pedestrians, horses, cars, and buses from Gabrielli and von Karman (11) and updated by Yong *et al.* (12); in addition, the figure presents measurements of the specific mechanical power of a walking lizard (5); the measured specific power for hexapod robots on a flat frictional and rough surfaces (4); and the specific power of the LRV and the MER

and MSL rovers based on electrical power, loads, and speeds (6–8). Overall, the performance of our machines does not match that of the walking animals. Hence, a better understanding of the underlying terrain such as that provided by the study by Li *et al.* may improve the performance of roving and walking robots.

MEDICINE

Spatial Turn in Health Research

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Developments in geographic science and technology can increase our understanding of disease prevalence, etiology, transmission, and treatment.

Spatial analysis using maps to associate geographic information with disease can be traced as far back as the 17th century. Today, recent developments and the widespread diffusion of geospatial data acquisition technologies are enabling creation of highly accurate spatial (and temporal) data relevant to health research. This

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Getting over the ground. The figure compares the dimensionless specific power ϵ , the vehicle power normalized by a product of the gross weight and the speed, with locomotion speed. The Gabrielli–von Karman line is an empirical fit of best performance data. Walking machines are still outperformed by animals, but the analysis by Li *et al.* may help in efforts to improve robot locomotion.

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