

these survivors and the establishment of new coral recruits (4). Recovery does not always occur, however, because corals weakened by the stress of bleaching may succumb to other factors, such as disease, or recruitment may fail. In St. Croix in the US Virgin Islands, for example, a major bleaching event in 2005 was followed by a disease outbreak that caused a 60% decline in live coral cover (7).

Given that temperatures will continue to increase for the foreseeable future, it is essential to know whether local management could improve reef prospects. Because poor water quality and overfishing are known to have killed many corals before bleaching became common (8, 9), it is widely accepted that reef recovery after bleaching could be improved by facilitating recruitment and regrowth; studies of the recovery of remote or well-managed reefs after bleaching (4, 10) support this idea. Unfortunately, however, according to the data from the Great Barrier Reef (5), the consensus has been that little could be done through management to reduce initial mortality from bleaching.

Recent data from a few locations in the Pacific (6, 11) as well as an earlier assessment from the Caribbean (8) suggest that this consensus might be too pessimistic. At Kiritimati Atoll, corals that acquired heat-tolerant symbionts after bleaching survived at higher rates, but this only occurred where anthropogenic stress was low (6). In Moorea, French Polynesia, higher nitrogen concentrations were associated with a doubling of bleaching severity at low levels of temperature stress (11). What Donovan *et al.* have done is to greatly expand confidence in the hypothesis that local management can make a difference, by performing a global analysis of the environmental factors that increase postbleaching mortality.

Their study, based on 223 reefs from the Caribbean and Indo-Pacific, documents substantially higher coral loss in the year after bleaching on reefs with high abundances of macroalgae and sea urchins, which are typically associated with overfishing and nutrient pollution. Because 1 year is likely too short a time to detect recovery from regrowth and recruitment (4), the higher loss rates must largely reflect mortality either during or shortly after the bleaching event. The effects described are highly important ecologically. For example, at some levels of heat stress, reefs with more macroalgae experience a 10-fold increase in mortality. In contrast to the earlier documentation of the effect of nitrogen on bleaching severity (11), the strength of the negative effect of macroalgae increases with the severity of the bleaching event.

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The data used in this study, from the Reef Check database, come from relatively simple reef surveys conducted by community and professional scientists and thus do not address the mechanisms underpinning these correlations. However, as the authors note, macroalgae are known to be detrimental to corals in a number of ways, and a variety of mechanisms could be responsible for the patterns observed. The relationship with sea urchin abundance is somewhat more surprising, because urchins, particularly in the Caribbean, are known to protect corals from overgrowth by macroalgae at moderate densities; hence, this probably reflects the negative impacts of extremely high amounts of grazing associated with urchin “barrens.” Better understanding of the mechanisms underpinning these and other patterns reported in this study will help to refine management approaches during the coming decade, when many reefs will continue to struggle.

Despite the doom and gloom of media reports on the state of the ocean, and the enormous challenges that remain, there is growing recognition that marine conservation actions have had measurable success (12, 13). Indeed, local actions can not only minimize damage from warming, but provide biodiversity and food-security benefits as well (12, 14).

This does not mean that taking the appropriate steps to, for example, reduce macroalgae and sea urchin abundance is easy in practice. Genuine stakeholder engagement is essential for conservation success (15); this is not simply a matter of resources, because establishing the required trust among stakeholders takes time and effort. The urgent need to slow and reverse climate change to save reefs from ecological extinction is also clear. During upcoming global negotiations, governments should remember that in addition to setting ambitious targets for lowering greenhouse gas emissions, empowering local communities to manage reef (and other) marine resources is an important strategy to reduce the negative impacts of climate change. ■

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BIOENGINEERING

Extracting electricity with exosuit braking

An exosuit lets wearers tense their muscles less and save energy in portions of their stride

By Raziel Riemer¹, Richard W. Nuckols², Gregory S. Sawicki^{3,4,5}

Exoskeletons and exosuits are wearable devices designed to work alongside the musculoskeletal system and reduce the effort needed to walk or run. Exoskeletons can benefit users by reducing the mechanical power and metabolic energy that they need to move about on the factory floor, in the rehabilitation clinic, on the playing field, and out at the shopping mall (1). Portable exoskeletons can use motors to add mechanical power into movement phases [net-positive exoskeleton power (2, 3)] or use springs to store and later return mechanical energy in a regenerative braking action [net-zero exoskeleton power (4, 5)]. On page 957 of this issue, Shepertycky *et al.* (6) describe a wearable assistive device that uses a generator to extract mechanical energy from the walking cycle (net-negative power) and convert it to electricity. At the same time, the walker actually uses less metabolic energy with the exosuit, saving on the cost to operate muscles as “biological brakes.”

Handgrip and pedal-powered dynamometers have long been in use and can convert mechanical power to electrical power, and these devices can have efficiencies as high as 70% (7). More recently, “hands-free” energy harvesters have been developed that can be worn on the back (8) or attached with an exoskeletal structure around the lower-limb joints (9–11). A performance metric for these devices is the cost of harvesting

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(COH), which is the ratio of the change in a user's metabolic power (measured in watts) when moving with versus without the device to the electrical power generated by the device. A positive COH means that the user must provide additional metabolic effort to generate electricity. For the examples above, the reported COH values have ranged from 4.8 for the back-mounted device (8) to 0.7 for a knee-joint mount (9).

This latter device developed by Donelan *et al.* (9) incorporated principles from fundamental movement biomechanics to strategically target phases of human walking where the lower-limb joints already resist motion (negative mechanical power) and behave effectively as brakes. Biomechanical analyses combining data from high-speed motion capture and instrumented force platforms with inverse-dynamics calculations reveal that the knee joint acts mostly like a brake during walking, especially at the end of the swing phase, when the foot is in the air (see the figure, top left). Muscles convert metabolic power to mechanical power with 25% ef-

iciency when acting as motors (positive mechanical power output) and -125% efficiency when acting as brakes (negative mechanical power output) (12).

Donelan *et al.* designed a knee exoskeleton in which a rotary generator attached in parallel with the human knee worked to help off-load biological braking. The resistance of the generator to turning provided the braking torque. With this device, they established that by targeting phases of negative mechanical power, exoskeletons can generate electricity with minimal increase in user effort. If muscles had acted as motors to provide the 1.7 W of mechanical power needed to generate each 1 W of electricity (their device had a 60% conversion efficiency), then users would have had to expend 6.8 W more metabolic power. However, for each 1 W of generated electricity, users only expended 0.7 W of metabolic energy (COH = 0.7). Although this system still required additional user effort, the results suggested that energy can be harvested from gait while at the same time saving metabolic energy—a negative COH.

This result highlights a key difference between skeletal muscle and engineered systems, namely, that braking is energetically cheap for machines (like a bicycle hand brake) but expensive for muscles, which have to consume metabolic energy to tense up and maintain braking force, especially when changing length (12). Thus, properly timed exoskeleton resistance could provide a portion of the negative muscle power that is normally lost as heat. Rather than requiring additional user effort to perform positive mechanical work on the exoskeleton generator, exoskeleton negative power would save the user the metabolic energy needed for muscle braking (13).

Shepertycky *et al.* designed a streamlined exosuit with a negative COH using a feedback-controlled “muscle-centric” loading profile. They specifically targeted the period during very late leg swing (just before the foot makes contact with the ground) when large braking forces are produced by actively lengthening hamstring muscles (for example, biceps femoris), rather than metabolically inactive passive elastic structures (for example, tendons and ligaments) (14). Their “traditional” loading profile (10) extracted the same total mechanical energy but resulted in a 3% metabolic penalty. The relatively subtle shift in timing and magnitude of the “muscle-centric” profile resulted in a 2.5% net metabolic benefit—a 5.5% improvement.

By strategically placing the device on the user's back, Shepertycky *et al.* were also able to reduce the carrying cost of their exosuit to just over 1%. This penalty is meager compared with the nearly 20% metabolic increase that was imposed by bulky knee-mounted exoskeletons that weighed 1.65 kg per leg (9). Their 1.1-kg device hardware rested at the waist near the user's center of mass. Exosuit support was supplied by tensioning cables that were routed along the posterior thigh and shank. The other ends of these cables were ultimately attached at the ankle to apply forces parallel to the hamstrings (see the figure, top middle).

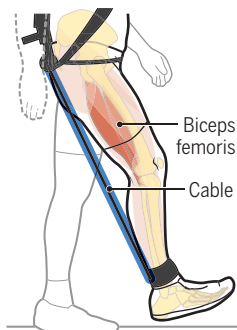
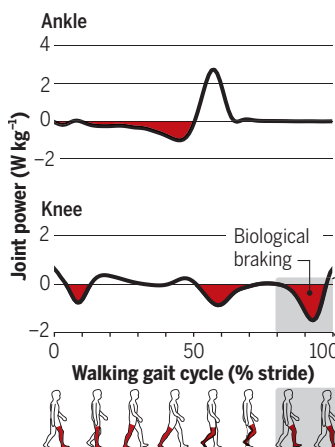
Shepertycky *et al.*'s energy-extracting exosuit, which achieves a net 2.5% reduction in the metabolic cost of walking along with 0.25 W of generated electricity, may only be the first of many such devices that could achieve a negative COH. Rough calculations based on engineering specifications for generators (7), locomotion biomechanics data (15), and fundamental muscle physiology relationships (12) suggest many opportunities to extend the principle of “resistive assistance” (see the figure, bottom). Targets include lower-limb joints other than the knee, gait phases other than terminal swing, and locomotion tasks other than walking on

Charging ahead by braking

Shepertycky *et al.* developed an exosuit that reduces the metabolic energy needed by muscles to resist motion during gait. A generator provides the “braking” force and produces electricity.

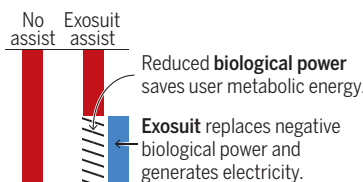
Taking power in stride

During a walking stride, the lower-limb joints inject and extract mechanical power [adapted from (15)].



Exosuit power recovery

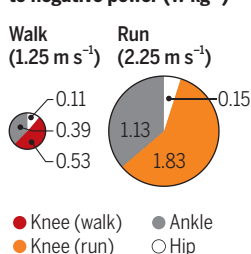
The exosuit of Shepertycky *et al.* uses a generator on the user's back connected by a cable to their ankle (blue line) to help muscles at the back of the thigh slow down the swinging leg in the late swing phase of walking (gray squares, left). The exosuit supplies a portion of the required knee-joint negative biological power (blue region) and reduces the amount of “biological braking” (red region in right bar), saving the user metabolic energy while generating electricity (blue bar).



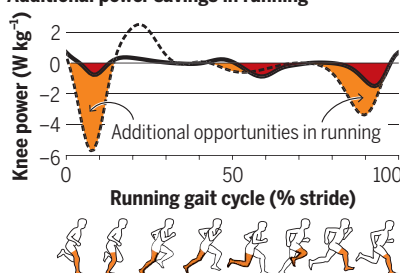
Harvesting on the run

Pie charts show the stride-average negative power for joints during level walking versus running, which requires more biological braking. A hypothetical running exosuit that supplants ~50% of knee biological braking could generate ~50 W of electricity.

Leg-joint contributions to negative power (W kg⁻¹)



Additional power savings in running



level ground. More intense gaits like running, where the legs cycle more positive and negative mechanical power, and tasks like walking downhill, descending staircases, or decelerating to a stop all provide increased opportunities for rigid exoskeletons or soft exosuits to assist the body's biological brakes while generating electricity.

The next-generation exosuits will begin to integrate physiological sensing systems and machine-learning algorithms to increase the versatility and impact of wearable assistive devices. During the next decade, a new challenge may be the development of an exosuit that minimizes human metabolic energy expenditure on a round-trip course spanning many kilometers over many days with access to a single onboard rechargeable battery. Optimal performance will likely require multijoint, hybrid support strategies that combine injection, extraction, and transfer of both electrical and mechanical energy to adapt continuously to locomotion-task demands and reduce metabolic energy expenditure of the user.

Such devices could have several applications, such as extending the range of on-foot search-and-rescue crews, outdoor adventurers, or soldiers on humanitarian missions. In the developing world, an exosuit could provide between 20 and 40% of the electricity needed per person on a typical day. The energy demands of portable electronics and increased recognition of the role of movement in longevity may drive exosuits toward widespread adoption. ■

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HYPOTHESIS

Making the hard problem of consciousness easier

Championing open science, an adversarial collaboration aims to unravel the footprints of consciousness

By Lucia Melloni^{1,2}, Liad Mudrik³, Michael Pitts⁴, Christof Koch^{5,6}

The history of science includes numerous challenging problems, including the “hard problem” (1) of consciousness: Why does an assembly of neurons—no matter how complex, such as the human brain—give rise to perceptions and feelings that are consciously experienced, such as the sweetness of chocolate or the tenderness of a loving caress on one's cheek? Beyond satisfying this millennia-old existential curiosity, understanding consciousness bears substantial medical and ethical implications, from evaluating whether someone is conscious after brain injury to determining whether nonhuman animals, fetuses, cell organoids, or even advanced machines (2) are conscious. A comprehensive and agreed-upon theory of consciousness is necessary to answer the question of which systems—biologically evolved or artificially designed—experience anything and to define the ethical boundaries of our actions toward them. The research projects described here will hopefully point the way and indicate whether some of today's major theories hold water or not.

After prosperous decades of focused scientific investigation zeroing in on the neural correlates of consciousness (3), a number of candidate theories of consciousness have emerged. These have independently gained substantial empirical support (4–7), led to empirically testable predictions, and resulted in major improvements in the evaluation of consciousness at the bedside (8, 9). Notwithstanding this progress, the conjectures being put forward by the different theories make diverging claims and predictions that cannot all be simultaneously true. Moreover, the theories evolve and continue to adapt as further data accumulates, with

hardly any cross-talk between them. How can we then narrow down on which theory better explains conscious experience?

The road to a possible solution may be paved by means of a new form of cooperation among scientific adversaries. Championed by Daniel Kahneman in the field of behavioral economics (10) and predated by Arthur Eddington's observational study to test Einstein's theory of general relativity against Newton's theory of gravitation (11), adversarial collaboration rests on identifying the most diagnostic points of divergence between competing theories, reaching agreement on precisely what they predict, and then designing experiments that directly test those diverging predictions. During the past 2 years, several groups have adopted this approach, following an initiative that aims to accelerate research in consciousness. So far, several theories of consciousness are being evaluated in this manner to test competing explanations for where and when neural activity gives rise to subjective experience.

The global neuronal workspace theory (GNWT) (4) claims that consciousness is instantiated by the global broadcasting and amplification of information across an interconnected network of prefrontal-parietal areas and many high-level sensory cortical areas. The sensory areas carry out different functions that range from feature processing to object or word recognition. Information in those sensory areas is processed in encapsulated modules, remaining unconscious. The frontal-parietal networks support integrative and executive functions, including selective attention and working memory. According to the GNWT, a stimulus must be attended to trigger activity that helps distribute this sensory information to many parts of the brain for further processing and report. It is this global broadcasting across many modules of specialized subsystems that constitutes consciousness. Conversely, the integrated information theory (IIT) (5) holds that consciousness should be understood in terms of cause-effect “power” that reflects the amount of maximally irreducible integrated information generated by certain neuronal architectures. On the basis of mathematical

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