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Glial cells for sensing pain in the skin *pp. 641 & 695*

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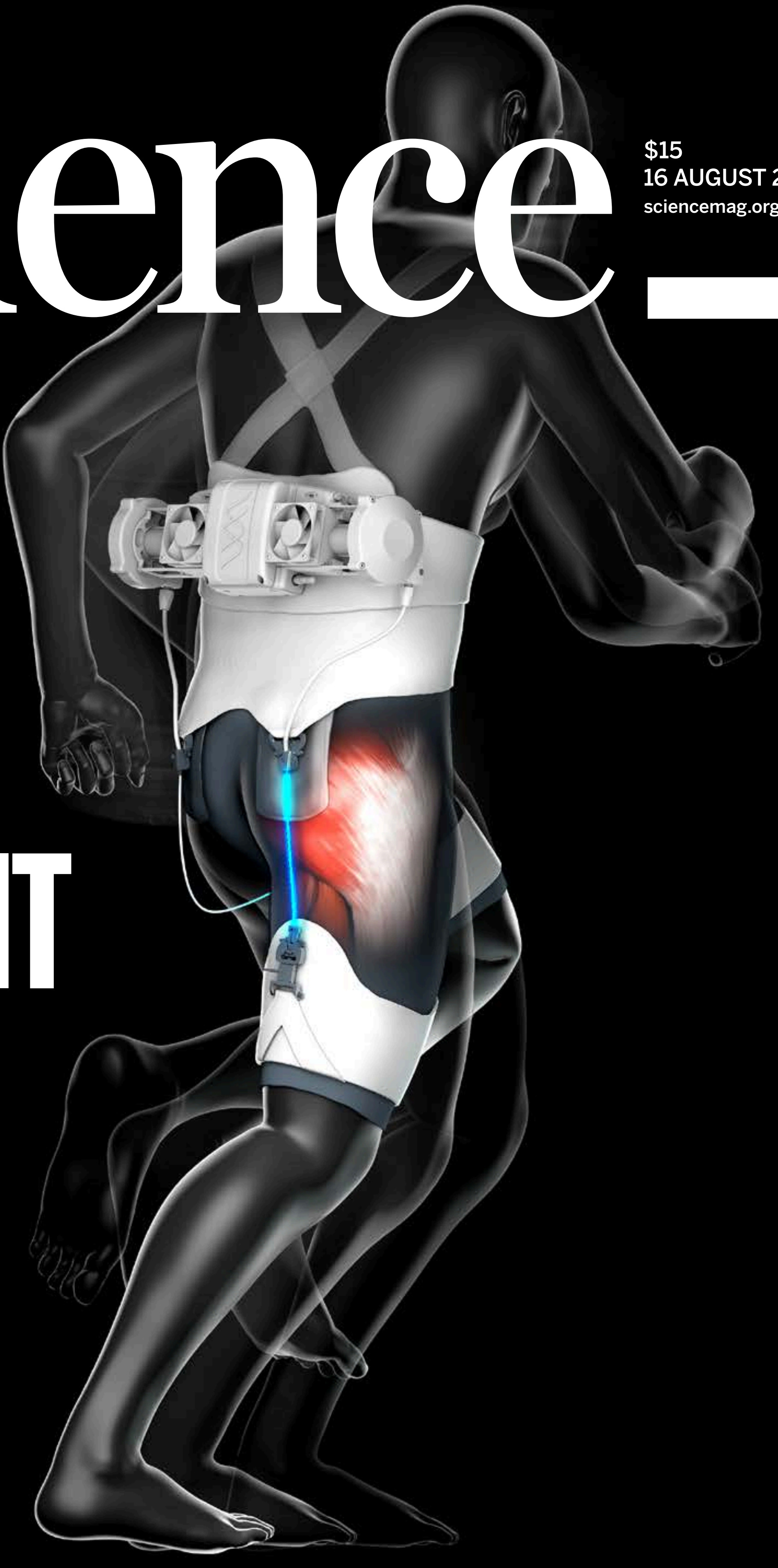

WALK-TO-RUN
EXOSUIT

Adaptive technology reduces metabolic cost of locomotion

pp. 636 & 668

ROBOTICS

Reducing the metabolic rate of walking and running with a versatile, portable exosuit

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Walking and running have fundamentally different biomechanics, which makes developing devices that assist both gaits challenging. We show that a portable exosuit that assists hip extension can reduce the metabolic rate of treadmill walking at 1.5 meters per second by 9.3% and that of running at 2.5 meters per second by 4.0% compared with locomotion without the exosuit. These reduction magnitudes are comparable to the effects of taking off 7.4 and 5.7 kilograms during walking and running, respectively, and are in a range that has shown meaningful athletic performance changes. The exosuit automatically switches between actuation profiles for both gaits, on the basis of estimated potential energy fluctuations of the wearer's center of mass. Single-participant experiments show that it is possible to reduce metabolic rates of different running speeds and uphill walking, further demonstrating the exosuit's versatility.

Humans can walk and run to attain a wider speed range. At low speeds, the metabolic rate of walking is lower than that of running, but this tendency is reversed at higher speeds, such that at high speeds the metabolic rate of running is lower than that of walking. The ability to switch between walking and running allows humans to adopt the gait with the lowest metabolic rate at each speed (fig. S1A) (*1*, *2*). Development of robotic assistive devices that can provide benefits for both walking and running is challenging because of the fundamentally different biomechanics of these gaits (*3*). In walking, the legs function like inverted pendulums to move the center of mass (CoM), and the gravitational potential energy and kinetic energy fluctuate out of phase (*4*). Running, meanwhile, can be modeled as a spring–mass system (*5*–*7*) with in-phase gravitational potential and kinetic energy fluctuations (*4*). In walking, the greatest internal joint moments occur at the ankle, and the hip and ankle perform approximately the same amount of positive work. In running, the greatest internal joint moments occur at the knee and ankle, and the ankle performs the largest amount of positive work, followed by the hip (*8*, *9*).

Because of these differences, most research laboratories have developed separate assistive devices for walking (*10*–*12*) and running (*3*, *13*–*15*). Robotic assistive devices have been shown to reduce the metabolic rate of walking below normal biological levels by 7 to 21% by assisting the ankle joint and/or the hip joint (*11*, *12*, *16*, *17*). Early efforts at reducing the metabolic rate of running have shown increases of 27 to 58% compared with running without an exoskeleton (*13*, *14*). These increases occur in part because the metabolic cost of carrying mass (e.g., a robotic assistive device) during running (*18*) is greater than that during walking (*19*, *20*), and the penalty for carrying mass on the limbs is further amplified due to increased limb acceleration (*21*, *22*). Nasiri *et al.* developed an unpowered exoskeleton that reduced the metabolic rate of running by 8% by applying an elastic torque at the hip as a function of interthigh angle (*23*). However, those authors noted that this design may not be effective during walking because it could disrupt the swing phase.

We hypothesize that assisting walking and running requires customized actuation profiles via an interface with low distal mass and minimal restriction of motion during the unassisted portions of the gait cycle. To achieve these design criteria, we use functional apparel to attach the device to the wearer, with cables that generate moments in concert with the combined moment that results from different biological muscles. We previously developed such an exosuit that reduces the metabolic rate of walking by 14.9% by assisting the ankle and hip (*16*). In the current study, we aimed to develop and test a lightweight, portable exosuit that assists with hip extension and can switch automatically between actuation profiles for walking and running. We chose to assist hip extension because it is important for both gaits (*8*, *9*, *24*) and does not require added mass to distal leg segments.

The textile components of the device consist of a waist belt and two thigh wraps (Fig. 1A, fig. S2, and data S1). Subjective testing of the maximum range of motion shows that the exosuit does not restrict the movements required for walking and running (Fig. 1B). Two electrical motors connected to cables via pulleys apply a tensile force between the waist belt and the thigh wraps to generate an external extension moment around the hip joint (movie S1 and data S2) (*3*). The entire exosuit weighs 5.0 kg, with 91% of the total system mass carried at the waist (table S1). This design approach minimizes the additional metabolic rate penalty when mass is added distally during walking (*25*) and running (*22*) (Fig. 1C). We programmed two separate actuation force profiles for walking and running. The timings of the walking profile and the running profile were selected on the basis of the profiles with the highest reduction in metabolic rate for walking (*26*) and running (*27*) in prior studies that used nonportable, tethered hip exosuits. The profile from the walking study was originally designed to approximate the biological hip extension moment, whereas the profile from the running study was designed to approximate the optimal profile from a muscle-driven simulation (*24*). Using these profiles as starting points, they were then slightly tailored to improve controller robustness and comfort through pilot tests. To allow the wearer to switch seamlessly between walking and running, we used an online classification algorithm that functions on the basis of potential energy fluctuations measured by inertial measurement units (IMUs) (Fig. 2, movie S1, and data S3) (*3*, *28*).

We conducted treadmill experiments at walking and running speeds ranging from 0.5 to 4.0 m s^{-1} and at gradients ranging from –10% to +20% with six male participants of similar age and build to assess the gait classification accuracy (*3*). The algorithm was 100% accurate at distinguishing between walking and running under all speed and incline conditions (data S4). Although the algorithm is based on vertical CoM acceleration at maximum hip extension, which is affected by slope, it worked accurately for steep inclines and declines.

We also conducted overground experiments on a paved outdoor course with gradual changes in speed and gait with eight male participants (fig. S3 and movie S2) (*3*). We found that the algorithm was 99.98% accurate in this protocol. Only two steps out of all trials were classified incorrectly, possibly due to altered CoM energy fluctuations in the first steps after a gait transition (Fig. 2B and fig. S4). A terrain that is more uneven than the paved outdoor course could alter the gait pattern (*29*, *30*) and affect the algorithm accuracy. However, an additional single-participant experiment on an outdoor course consisting of sloped terrain and different unpaved surfaces (mud, snow) showed 100% accuracy under such conditions (fig. S5) (*3*). Other gait classification algorithms have been developed

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for activity logging (*31*) and controlling robotic leg prostheses (*32*), but similar accuracy has not yet been demonstrated in an exoskeleton or exosuit. Gait classification in exoskeletons or exosuits involves certain challenges, because the actuation can affect the gait pattern, which in turn can affect gait classification accuracy. To highlight the importance of accurate gait classification and gait-specific assistance, we conducted another single-participant experiment during which we applied the walking actuation profile during running and vice versa. We found that applying the opposite actuation profile deteriorated controller performance and increased metabolic rate by 33.9% (Fig. 3C) when tested during a combined walking and running condition (*3*).

The effects of the exosuit on metabolic rate during treadmill walking at 1.5 m s^{-1} and running at 2.5 m s^{-1} were evaluated on nine participants who had prior experience wearing the exosuit, as prior studies with other robotic assistive devices highlighted the importance of experience for participants to maximize the benefit they achieved from robotic assistive devices (*10*, *33*, *34*). Participants walked and ran while wearing the exosuit with assistance turned on (assist on), with assistance turned off (assist off), and without wearing the exosuit (no exo). The metabolic rate with exosuit assistance was reduced by 9.3 ± 2.2% (SEM; $P = 0.005$) for walking and by 4.0 ± 1.3% (SEM; $P = 0.017$) for running compared with that in locomotion without the exosuit ($n = 9$ participants, two-sided paired t tests with Holm-Šidák correction) (Fig. 3, A and B, and table S2) (*3*). In a previous overground experiment, we also found a reduction of 3.9 ± 1.0% (SEM; $P = 0.015$) in metabolic rate during running but no reduction ($P = 0.536$) during walking, possibly due to less strictly controlled experimental conditions ($n = 8$, two-sided paired t tests with Holm-Šidák correction) (table S3) (*3*). Additional single-participant treadmill experiments showed that it is possible to reduce the metabolic rate during higher-intensity locomotion conditions, such as walking at 1.5 m s^{-1} up a 10% slope or level running at different speeds up to 3 m s^{-1} (Fig. 3, D and E).

The mean reduction in metabolic rate of 9.3% during level treadmill walking is lower than best-in-class reductions for tethered devices [17.4% (*35*)] and powered portable devices [21.1% (*17*)] during walking and is similar to the reduction obtained with unpowered portable devices during walking [7.2% (*12*)]. The mean reduction of 4.0% in treadmill running at 2.5 m s^{-1} is of a similar magnitude as the previous best-in-class reduction obtained with a similar tethered hip exosuit [5.0% (*27*)] but about half as much as the reduction obtained with an unpowered portable hip exoskeleton [8.0% (*23*)]. The interparticipant

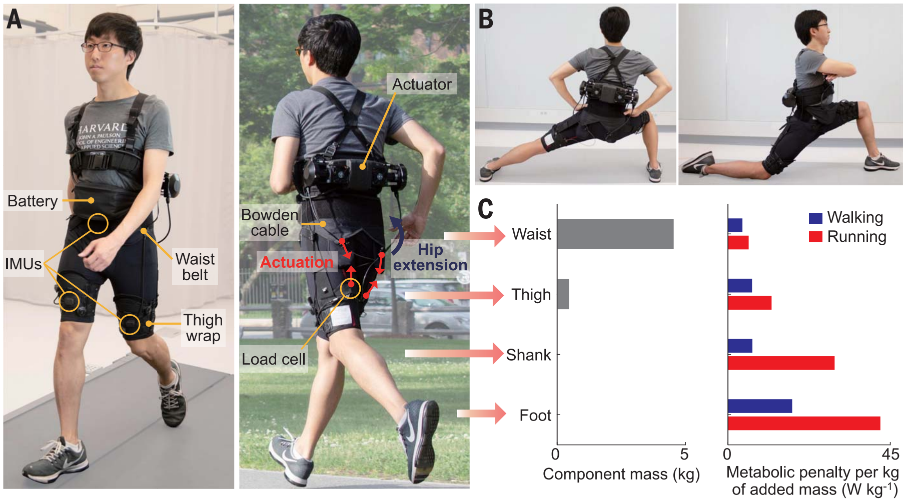

Fig. 1. Exosuit. (**A**) Components of the exosuit shown during treadmill walking and overground running. (**B**) Demonstration of the range of motion allowed by the exosuit. (**C**) Component mass and estimated penalty per kilogram of added mass for each segment, based on coefficients from the literature (table S1). The exosuit mass is concentrated around the waist, where the metabolic penalty per kilogram of added mass is the lowest. Components and mass distribution data are shown in table S1 and fig. S2. The operation of the exosuit is shown in movie S1.

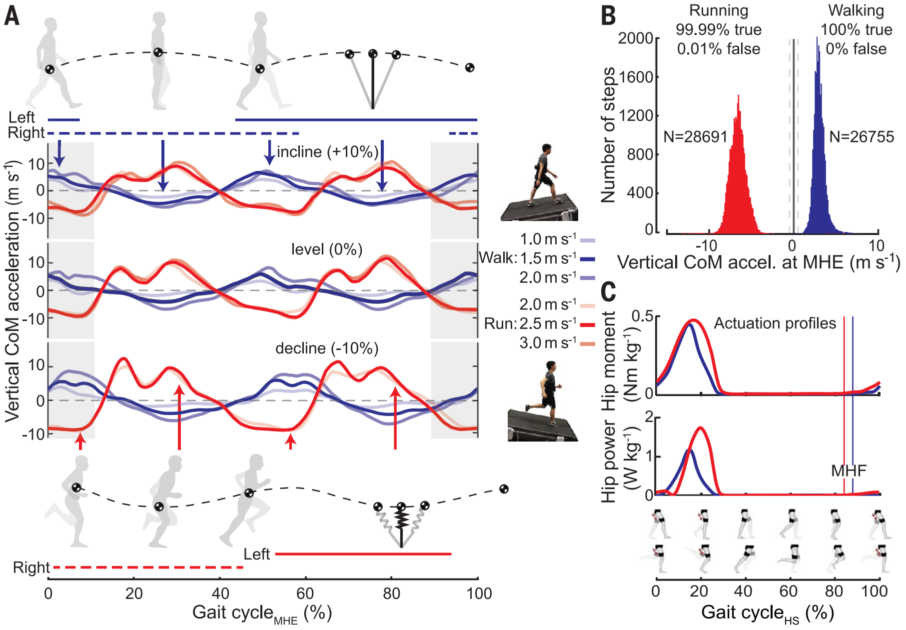

Fig. 2. Biologically inspired gait classification algorithm and actuation. (**A**) Vertical CoM acceleration during walking and running on a treadmill at different slopes and speeds ($n = 1$). Acceleration is measured by an abdomen IMU and segmented into strides on the basis of detection of maximum hip extension (MHE) via thigh IMUs. Horizontal lines represent the stance phases. The gray shaded area indicates the region used for classification. (**B**) Histogram of vertical CoM acceleration at maximum hip extension for all treadmill and overground protocols ($n = 23$). The vertical lines indicate thresholds used for classification. (**C**) Actuation profiles for walking (blue) and running (red) that were applied during the physiological and biomechanical testing on a treadmill ($n = 7$). The vertical line indicates the detection of maximum hip flexion (MHF) via thigh IMUs. Actuation profiles are segmented into strides on the basis of heel strikes (HS). Algorithm pseudocode and data of the gait classification experiments are provided in data S3 and S4.

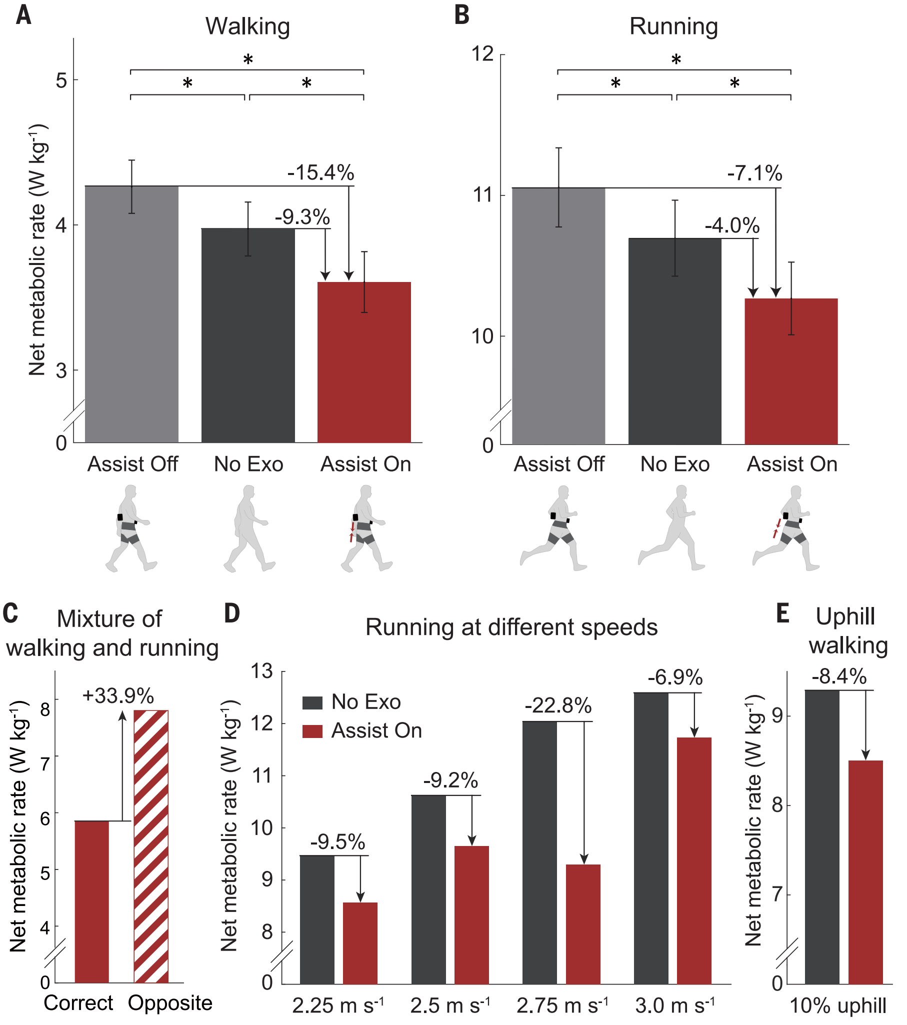

Fig. 3. Metabolic rate. (**A** and **B**) Metabolic rate for level walking at 1.5 m s^{-1} (A) and level running at 2.5 m s^{-1} (B) during the treadmill physiological and biomechanical testing protocol. Bars represent walking and running with the assistance turned off (assist off), without wearing the exosuit (no exo), and while wearing the exosuit with assistance turned on (assist on). Error bars indicate SEM. Asterisks indicate statistically significant differences ($n = 9$, two-sided paired t tests with Holm-Šidák correction, $P < 0.05$). (**C** to **E**) Metabolic rates from single-participant experiments for combined level walking and running bouts with correct or opposite actuation profiles for each gait (C), level running at different speeds (D), and 10% uphill walking at 1.5 m s^{-1} (E) ($n = 1$). Individual metabolic data are available in table S2.

variability of the reduction in metabolic rate during treadmill running was sizable but within the range of variabilities found in similar studies (*23*, *27*).

Humans may adapt to assistance at the hip joint by changing their coordination. To understand the effects of the actuation profiles that underlie the metabolic rate reductions, we compared differences between assist-on and assist-off conditions. We calculated the biological component of the hip moment by subtracting the moment of the exosuit from the total joint moment computed using inverse dynamics analysis of motion capture measurements in seven of the nine participants. As expected, during walking, the assist-on condition reduced the peak biological hip extension moment compared with the assist-off condition. The reduction was 14% [−0.128 ± 0.020 N·m kg^{-1} (SEM); $n = 7$, two-sided paired t test, $P < 0.001$] (Fig. 4A, table S4, and data S5). During running, there was a trend toward a reduction in peak biological hip extension moment in the assist-on compared with the assist-off condition by 12% [−0.168 ± 0.072 N·m kg^{-1} (SEM); $n = 7$, two-sided paired t tests, $P = 0.059$] (table S5). The assist-on condition reduced the peak hip extensor (gluteus maximus) activation during walking compared with the assist-off condition (−14%; $n = 7$, two-sided paired t tests, $P = 0.043$).

Even though the exosuit applied hip extension moments, it is possible that a portion of the reduction in metabolic rate comes from joints other than the hip. Muscle-driven simulations from another research laboratory predicted that robotic assistive devices can reduce activity in muscles that do not cross the assisted joints (*24*). Additionally, prior experimental work has shown that ankle exoskeletons can have effects on joints other than the ankle (*36*). In our experiment, the assist-on condition reduced the peak internal knee extension moment compared with the assist-off condition during walking and running (−12 and −3%; $n = 7$, two-sided paired t tests, $P = 0.038$ and 0.046) (Fig. 4B) and caused a trend toward reduced peak knee extensor (vastus lateralis) activation compared with that for the assist-off condition during running (−6%; $n = 7$, two-sided paired t test, $P = 0.082$). For walking, this phenomenon could be related to a reduction in knee flexion angle compared with that for the assist-off condition ($n = 7$, two-sided paired t test, $P = 0.041$), resulting in a reduction of the product of the ground reaction force and its moment arm with respect to the knee ($n = 7$, two-sided Wilcoxon signed rank test, $P = 0.031$) (Fig. 4C). This product is related to terms that add up to the total knee moment. Such an indirect strategy of assisting the knee via the hip could have applications in populations in which assisting the knee directly is challenging, such as above-the-knee amputees who rely on hip extension to compensate for the lack of knee function (*37*).

During walking, the assist-on condition also led to reductions in peak plantar flexor muscle activations (−4.5% for gastrocnemius medialis, −7.6% for soleus; $n = 7$, two-sided paired t test, $P = 0.038$ and 0.081, respectively) and an increase in stride frequency compared with the assist-off condition (+3.1%; $n = 7$, two-sided paired t test, $P = 0.007$) (table S4). This greater stride frequency may result from the exosuit actuation decelerating the swing leg before heel strike, and it may be related to the observed changes in joint moments and muscle activations during stance (*38*, *39*).

To evaluate if wearing the passive structure of the exosuit affected gait, we compared the range of motion and the effects of added mass between the assist-off and no-exo conditions. We found reductions of 2° ± 1° (SEM) in the hip range of motion for the assist-off compared with the no-exo condition in the sagittal plane during walking and in the coronal plane during running ($n = 7$, two-sided paired t tests, $P = 0.020$ and 0.010) (Fig. 4D). We found no significant differences in any other planes during walking and running ($n = 7$, two-sided paired t tests, $P > 0.111$ for all other comparisons). These differences also may have been a result of marker repositioning errors between the assist-off and no-exo conditions, but overall they highlight the minimally restrictive nature of the exosuit. The assist-off condition increased the metabolic rate by 7.0 and 3.3% [22 ± 7 and 28 ± 3 W (SEM)] above that for the no-exo condition during walking and running, respectively ($n = 9$, two-sided paired t tests with Holm-Šidák correction, $P = 0.002$ and <0.001). These increases are not significantly different from the weight penalty estimated from literature prediction formulas ($n = 9$, two-sided paired t tests, $P = 0.972$ and 0.260) (tables S1 and S6).

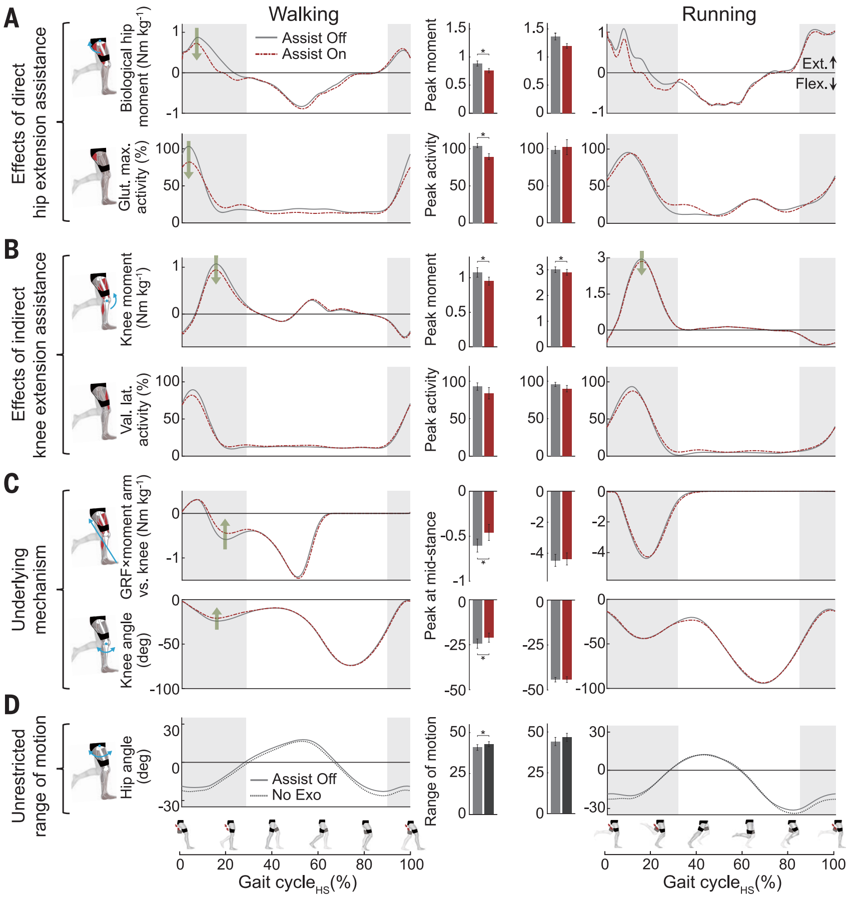

Fig. 4. Biomechanical analyses during treadmill protocol. (**A**) Effects of direct hip extension assistance on biological hip moment and gluteus maximus activation. (**B**) Effects of indirect knee extension assistance on internal knee moment and vastus lateralis activation. (**C**) Underlying mechanism. Reduction in internal knee moment could be related to decreased knee flexion, which causes a reduction of the product of the ground reaction force (GRF) and the moment arm from the knee. (**D**) Hip range of motion. All time series plots show population averages as a function of gait cycle. All extension angles and moments are positive. Green arrows indicate peak values that are analyzed in bar plots. Error bars indicate SEM. Gray shaded regions indicate the actuation period of the exosuit. Asterisks indicate statistically significant differences ($n = 7$, two-sided paired t tests, $P < 0.05$). Other joint- and muscle-level biomechanical summary metrics are shown in tables S4 and S5. Individual source data are available in data S5.

This work demonstrates a lightweight and minimally restrictive robotic assistive device that can reduce the metabolic rate of both walking and running. By automatically adapting assistance to the activity, the system allows the wearer to use their preferred gait for each speed. Thus, the exosuit leverages the biological versatility of human locomotion, thereby providing advantages of a wider speed range at a lower metabolic cost of transport than devices that only assist a single gait (fig. S1). To put the results in perspective, the metabolic rate reductions during walking can be compared to the effect of taking off 7.4 kg at the waist (*25*) or to reductions in metabolic rate from restorative surgery in children with cerebral palsy (*40*). The metabolic rate reductions during running can be compared to the effect of taking off 5.7 kg at the waist (*41*) or the effects of a recently designed running shoe with improved energy return (*42*). Although the changes in metabolic rate are relatively modest, they are of similar magnitude to those that have proven to be sufficient to produce changes in maximum walking and running performance. One study by Galle *et al.* (*43*) showed that an exoskeleton that reduces the metabolic rate of submaximal uphill walking by 8% significantly increases maximum performance in an incremental load test by an equal amount. Another study by Hoogkamer *et al.* (*44*) showed that increases in shoe mass that increase metabolic rate by 3.5% lead to a significant deterioration in time trial performance. Therefore, we hypothesize that our 9.3 and 4.0% reductions in the metabolic rates of walking and running, respectively, could result in proportional increases in maximal performance, for example, over a cross-country course. Moreover, additional single-participant experiments show that the exosuit is capable of providing assistance during more challenging locomotion conditions (e.g., on uphill slopes or unpaved terrain), further highlighting the versatility of the system.

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SUPPLEMENTARY MATERIALS

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Materials and Methods
Supplementary Text
Figs. S1 to S5
Tables S1 to S7
References (*45*–*88*)
Movies S1 to S3
Data S1 to S6

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Science

Reducing the metabolic rate of walking and running with a versatile, portable exosuit

Jinsoo Kim, Giuk Lee, Roman Heimgartner, Dheepak Arumukhom Revi, Nikos Karavas, Danielle Nathanson, Ignacio Galiana, Asa Eckert-Erdheim, Patrick Murphy, David Perry, Nicolas Menard, Dabin Kim Choe, Philippe Malcolm and Conor J. Walsh

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Lowering locomotion's metabolic cost

Walking and running require different gaits, with each type of motion putting a greater bias on different muscles and joints. Kim *et al.* developed a soft, fully portable, lightweight exosuit that is able to reduce the metabolic rate for both running and walking by assisting each motion via the hip extension (see the Perspective by Pons). A waist belt holds most of the mass, thus reducing the cost of carrying the suit. By tracking the motion of the user, the suit is able to switch modes between the two types of motion automatically.

Science, this issue p. 668; see also p. 636

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