SCIENCE ROBOTICS | FOCUS

ASSISTIVE DEVICE

Reducing the metabolic cost of running with a tethered soft exosuit

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Assisting hip extension with a tethered exosuit and a simulation-optimized force profile reduces metabolic cost of running.

Through evolution, our human species has become remarkably good at distance running thanks to long spring-like tendons in the legs and hairless skin for optimal thermoregulation. Studies have shown that distance running performance is linearly correlated with metabolic cost, and there has been an increased interest in the robotics community to develop wearable exoskeletons to further augment human performance by reducing metabolic cost.

The past 3 years have seen exciting breakthroughs in exoskeletons that are able to reduce the metabolic cost of walking (*1*–*4*); however, to date, efforts to develop exoskeletons that assist running have been limited, and initial studies have not yet been able to demonstrate reductions in metabolic cost (*5*, *6*). One of the challenges with developing exoskeletons to assist running is that biological joint work in running is greater than in walking. Another challenge is that the metabolic cost of carrying weight at the waist or distally is higher during running than during walking; therefore, the metabolic penalty of the weight of an exoskeleton is more likely to offset the effects of the assistance.

Due to limited studies on assisted running, we do not yet know which joint is best in assisting and which moment profile is optimal. A common thought in the field of exoskeleton research over the previous decade is that assistance profiles should mimic the biological moments. However, in recent studies on walking, it has been demonstrated that higher reductions in metabolic cost can be achieved by exploring the metabolic landscape of the wearer by conducting parameter sweeps to identify the optimal actuation profiles (*1*, *2*, *7*, *8*).

Recently, Uchida *et al.* proposed the use of musculoskeletal simulations to predict the effects of different assistance profiles on metabolic cost during running (*9*). Interestingly, they found that the optimal assistive moment profile does not necessarily mimic the biological joint moment, which they attribute to the fact that muscle activity can be reduced beyond the joint being assisted. Similar findings have been experimentally demonstrated with assisted walking (*1*).

In this article, we extend our previous work on soft exosuits for running and follow an experimental protocol similar to our past work on assisted walking with an off-board actuation system (*8*). Exosuits use functional apparel to comfortably and securely anchor to the human body and apply joint moments via tensile forces across joints in parallel with the muscles. Actuation was applied with an off-board system to isolate the relationship between assistance profile and metabolic reduction, without the effect of actuator mass. While a limitation of this approach is that the entire system mass is not worn, this study can be used as a first step in understanding the effects of different types of assistance on metabolic cost.

We analyzed data from eight male participants (27.1 ± 3.1 years, 79.3 ± 9.7 kg, 1.82 ± 0.63 m) during running at 2.5 m s^{-1} on a treadmill. After a habituation session, we performed a series of experiments in which we evaluated the effects of two hip extension assistance profiles: A profile that mimics the biological hip moment based on reference data (Scaled-biological) and a profile that was inspired by the simulation study from Uchida *et al.* (Simulation-optimized) (*9*). We compared the effects of both profiles to running without the exosuit (No-suit) and to running with the exosuit powered off (Powered-off).

The version of the soft exosuit used in this study is similar to the one previously presented by Ding *et al.* (Fig. 1A) (*10*). Both Simulation-optimized and Scaled-biological provided a peak moment of 0.380 N m kg^{-1} but in Simulation-optimized the actuation occurred later in the stride (Fig. 1B). Metabolic cost was assessed by indirect calorimetry (Cosmed, Rome, Italy). We measured joint angles with IMUs (Xsens, Enschede, Netherlands, and VectorNav, TX, USA) placed on the foot, shank, and thigh and ground reaction force with an instrumented treadmill (Bertec, Columbus, OH). Repeated measures analysis of variance (ANOVA) was conducted across four conditions (Powered-off, No-suit, Scaled-biological, and Simulation-optimized) to verify the effect of hip extension assistance on metabolic cost and gait parameters, with significance set at $P \leq 0.05$.

Simulation-optimized and Scaled-biological reduced metabolic rate with respect to Powered-off by 9.1 ± 2.2% ($P < 0.001$) and 5.0 ± 2.4% ($P < 0.001$), respectively (Fig. 1C). Simulation-optimized also reduced metabolic rate by 5.4 ± 4.2% ($P = 0.001$) compared to No-suit. Powered-off increased metabolic cost compared to No-suit by 4.1 ± 4.4% ($P = 0.013$).

We found a higher metabolic cost reduction using a Simulation-optimized actuation profile (*9*) compared to a profile based on Scaled-biological hip moment data. Although we could not verify reductions in muscle activity, we found indications that Simulation-optimized indirectly affected other lower limb joints. More specifically, Simulation-optimized increased peak knee extension and increased the braking and propulsion impulse of the ground reaction force compared to Powered-off, whereas Scaled-biological did not show these changes (see the Supplementary Materials). In the field of robotics in general and wearable robotics in particular, a lot of successful developments have been based on mimicking biological design or control strategies. Our finding supports a paradigm shift toward the concept that biological is not necessarily always optimal.

In conclusion, we found that it is possible to reduce metabolic cost of running by

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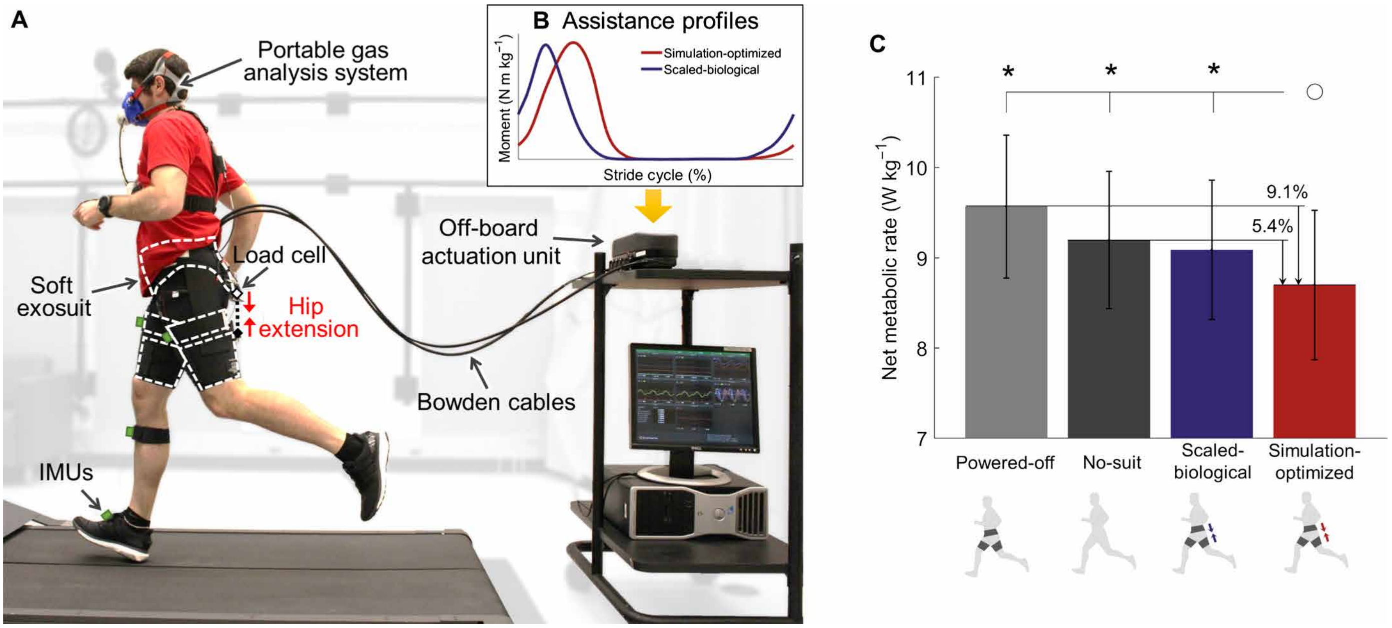

Fig. 1. Measuring motions, moments, and metabolism. (**A**) Experimental setup. While a participant is running with the soft exosuit, an off-board actuation system generates assistive forces and Bowden cables transfer the forces to the exosuit. We measured exosuit forces (load cells), segment motions (IMUs), ground reaction forces (instrumented treadmill), and metabolic rate (indirect calorimetry). (**B**) Moment profile conditions. Lines represent exosuit moment versus stride time. Red is Simulation-optimized based on Uchida *et al.* (*9*), and blue is Scaled-biological (see the Supplementary Materials for details of profiles). In Simulation-optimized, the assistance started at 12% before initial foot contact, reached a peak at 21%, and continued until 40% of the stride. In Scaled-biological, the assistance started at 15% before initial foot contact, reached a peak at 10%, and continued until 32% of the stride. (**C**) Net metabolic rate. Colors indicate running conditions shown in pictograms. Error bars are SD. Net metabolic rates were 9.57 ± 0.79, 9.20 ± 0.76, 9.09 ± 0.77, and 8.70 ± 0.83 W kg^{-1} for Powered-off, No-suit, Scaled-biological, and Simulation-optimized, respectively. *$P \leq 0.05$.

5.4% with hip extension assistance from a tethered soft exosuit compared with when not wearing the exosuit. Because the ultimate goal of this research is to reduce metabolic cost during overground running, development of a body-worn system that includes all actuation and control hardware is required. Actuation approaches that have a high power-to-weight ratio will be critical so that the benefit to the wearer offsets the carried mass penalty. Based on our results here and mass penalty equations from the literature, we can estimate a system that should weigh less than 5 kg (see the Supplementary Materials), which seems reasonable based on past work (*1*, *3*). Beyond actuation, there are exciting possibilities to further refine the attachment to the wearer to enable higher and more efficient power transfer as well as develop control approaches that enable individualization of assistance through approaches such as human-in-the-loop optimization.

SUPPLEMENTARY MATERIALS

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Materials and Methods
Table S1. Exosuit actuation parameters.
Table S2. Biomechanical parameters.
Movie S1. Participant jogs under experimental conditions.
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Acknowledgments: We thank M. Athanassiu, Y. Ding, A. Eckert-Erdheim, D. Ryan, and D. Wagner for their help. **Funding:** This research is supported by the DARPA (W911NF-14-C-0051), NSF (CNS-1446464), Samsung (scholarship J.K.), Wyss Institute, and Harvard Paulson School. **Competing interests:** C.J.W. is author of patent applications U.S. 9,351,900, U.S. 14/660,704, U.S. 15/097,744, U.S. 14/893,934, PCT/US2014/068462, and PCT/US2015/051107 filed by Harvard University and licensed by ReWalk Robotics.

10.1126/scirobotics.aan6708

Citation: G. Lee, J. Kim, F. A. Panizzolo, Y. M. Zhou, L. M. Baker, P. Malcolm, C. J. Walsh, Reducing the metabolic cost of running with a tethered soft exosuit. *Sci. Robot.* **2**, eaan6708 (2017).

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Sci. Robotics **2**, eaan6708.
DOI: 10.1126/scirobotics.aan6708