Reducing Metabolic Cost During Planetary Ambulation Using Robotic Actuation

Logan Kluis; Nathan Keller; Hedan Bai; Narahari Iyengar; Robert Shepherd; Ana Diaz-Artiles

INTRODUCTION: Current spacesuits are cumbersome and metabolically expensive. The use of robotic actuators could improve extravehicular activity performance. We propose a novel method to quantify the benefit of robotic actuators during planetary ambulation.

METHODS: Using the OpenSim framework, we completed a biomechanical analysis of three walking conditions: unsuited, suited with the extravehicular mobility unit (EMU) spacesuit (represented as external joint torques applied to human joints), and suited with the EMU and assisted by robotic actuators capable of producing up to 10 Nm of torque. For each scenario, we calculated the inverse kinematics and inverse dynamics of the lower body joints (hip, knee, and ankle). We also determined the activation of muscles and robotic actuators (when present). Finally, from inverse dynamics and muscle activation results, the metabolic cost of one gait cycle was calculated in all three conditions.

RESULTS: The moments of lower body joints increased due to the increased resistance to movement from the spacesuit. The additional torque increased the overall metabolic cost by 85% compared to the unsuited condition. The assistive robotic actuators were able to reduce the metabolic cost induced by EMU resistance by 15%.

DISCUSSION: Our model indicates that the majority of metabolic cost reduction can be attributed to the actuators located at the hip. The robotic actuators reduced metabolic cost similar to that of modern-day actuators used to improve walking. During a Mars mission, the actuators could save one crewmember up to 100,000 kilocal on one 539-d planetary expedition.

KEYWORDS: SmartSuit, metabolic cost, energy expenditure, human performance, musculoskeletal modeling.

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Current gas-pressurized spacesuits are cumbersome, cause fatigue and injuries,[12] and are metabolically expensive.[25] The current NASA spacesuit (the extravehicular mobility unit or EMU) operates in microgravity environments at 4.3 psia and 100% oxygen, and was not designed to operate on planetary surfaces.[12] The EMU hard upper torso (HUT) is available in three sizes and connects to interchangeable parts to fit a range of astronaut sizes, which differs from the Apollo spacesuits which were custom made for individual astronauts. The accommodation to fit a wider range of astronaut sizes has led to spacesuits that do not optimally fit the entire astronaut population properly. As a result, injuries have increased due to elevated pressure at contact points when astronauts attempt to use the spacesuit's full range of motion.[3,4] Increased strength is needed to generate the required joint torques to operate within the highly pressurized spacesuit environment.[27] The additional effort may also cause discomfort, fatigue, and increased energy expenditure, which directly impacts the capabilities of the life support system and, therefore, overall mission objectives. The accumulation of difficulties from poor fit, limited range of motion, injuries, and high metabolic expenditure may lead to suboptimal extravehicular activity (EVA) performance and impact mission success.[13]

Robotic actuation has the potential to reduce the metabolic cost of gas-pressurized spacesuits. Robotic elements can counteract resistive spacesuit joint torques and therefore improve mobility and augment human performance during surface

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exploration. The use of robotics in spacesuits has traditionally focused on hand exoskeletons as the fatigue and difficulty of repetitive squeezing motions has led to a disproportionate number of EVA injuries occurring on the hand.[24,28] Minimal research has been completed for use on major joints in spacesuit motions such as elbow flexion/extension[34] and knee flexion/extension.[23] Larger actuators, such as those used for the arms and legs, are difficult to integrate into a spacesuit because of the difficulty of making the actuator work precisely with human motions. As a result, extensive work is still needed to incorporate the control dynamics for a single joint in a specific walking motion.[23]

More commonly, exoskeletons have been used to simulate the resistive joint torques from spacesuits during EVA.[8,26] The exoskeletons can then be used to replicate the conditions of walking in a spacesuit at varying speeds and gravity levels.[9] Employing exoskeletons as a simulation tool for suited motion allows for a less expensive testing methodology that removes the need for pressurized garments and permits the observation of the limbs. Unfortunately, these exoskeletons have been limited to reproduce knee torques only.[8,26] Although spacesuit knee joints are hypothesized to act as springs during ambulation, suited planetary walking motions would also likely make use of hip flexion/extension and abduction/adduction.

In this context, we developed a new musculoskeletal modeling framework to quantitatively assess human performance benefits associated with introducing general lower-body actuation into gas-pressurized spacesuits. While previous studies have investigated the introduction of robotic elements in specific parts of the spacesuit or developed an exoskeleton to model spacesuit torques, this is the first attempt to quantify the impact of lower body actuation on a suited walking motion. We conducted biomechanical and metabolic expenditure simulations during a walking motion in unsuited conditions and suited conditions with and without assistive robotic components in multiple lower body joints. This investigation fits within the framework of a novel spacesuit architecture for EVA operations on planetary surfaces called SmartSuit. The SmartSuit, while still a gas-pressurized spacesuit, incorporates a full-body soft-robotic layer that increases astronaut mobility, therefore decreasing metabolic expenditure and facilitating exploration operations.[15] We hypothesize that the use of robotic components will decrease the metabolic expenditure during suited planetary ambulation.

METHODS

Modeling Human-Spacesuit Interaction

A new computational framework was developed in OpenSim[10] to investigate human performance during planetary traverses. We implemented a walking motion using a three-dimensional musculoskeletal model containing 54 linear muscle actuators and 23 degrees of freedom, representing an astronaut model of 1.8 m in height and 75 kg of weight. The development and limitations of the model are further described by Delp et al.[11] This model is freely available to the OpenSim community and has been used in similar research efforts.[14] Three walking conditions were modeled: unsuited, suited with resistive EMU joint torques (EMU), and suited with resistive EMU joint torques and additional assistive robotic actuators (EMU-assisted).

To simulate external EMU spacesuit torques, we used the most comprehensive database of experimental EMU spacesuit joint torque-angle relationships collected using empty but pressurized spacesuits and an instrumented robot inside the spacesuit.[18,31] Since we were interested in locomotion, we focused on the ankle, knee, and hip joints. Joint torque-angle relationships also exist for the Mark III spacesuit, which is a technology demonstration spacesuit built for planetary EVAs. We chose to use the EMU spacesuit instead of the Mark III because a more comprehensive data set exists for the EMU spacesuit (joint torque-angle relationships for the hip joints are not available for the Mark III spacesuit). The first column in **Fig. 1** shows the four lower body EMU joint torque-angle relationships implemented in our simulations: ankle dorsiflexion/plantarflexion, knee flexion/extension, hip flexion/extension, and hip abduction/adduction. It is important to note that the magnitude and direction of the joint torque-angle relationship is dependent on the direction of motion. For example, knee flexion follows a different joint torque-angle relationship than that of knee extension as can be seen in Fig. 1D. From this relationship, we can calculate the resistive spacesuit joint torque at a given joint angle during a walking motion. The middle column shows the kinematics for the lower body joints as they progress through one gait cycle. The resulting applied spacesuit torques are shown in the last column. Using Fig. 1A as an example, the EMU ankle torque is displayed as a function of the ankle angle (α) with $\alpha = 0$ representing the foot at a perfect right angle from the tibia. As the ankle begins dorsiflexion, the ankle angle increases (represented by an increase in α). At $\alpha = 20°$, the torque reaches 3 Nm. As the ankle begins plantarflexion, α decreases and the EMU ankle joint torque decreases accordingly. For reference, the ankle angle during the walking motion used for our simulations reached a maximum of ~13°. At this point, the EMU would apply a torque of approximately 2 Nm during dorsiflexion and negative 1 Nm during plantarflexion. The ankle dorsiflexion/plantarflexion torque hysteretic shape is shared by the other three torque-angle relationships and is similar to those found from the knee and ankle on other spacesuits such as the Mark III.[35]

In addition to the resistive EMU joint torques, the EMU-assisted condition also included robotic actuators capable of achieving up to 10 Nm of torque in each one of the four joints described above (ankle dorsiflexion/plantarflexion, knee flexion/extension, hip flexion/extension, and hip abduction/adduction) to assist in walking and minimizing the impact of spacesuit resistance. The 10-Nm torque limit was chosen based on preliminary testing of soft-robotic actuators being developed for the SmartSuit concept and an outline of the testing can be found elsewhere.[15]

Musculoskeletal Modeling Platform

We implemented our analysis in OpenSim, an open-source biomechanical software with a large variety of capabilities, including inverse kinematics (IK), inverse dynamics (ID),

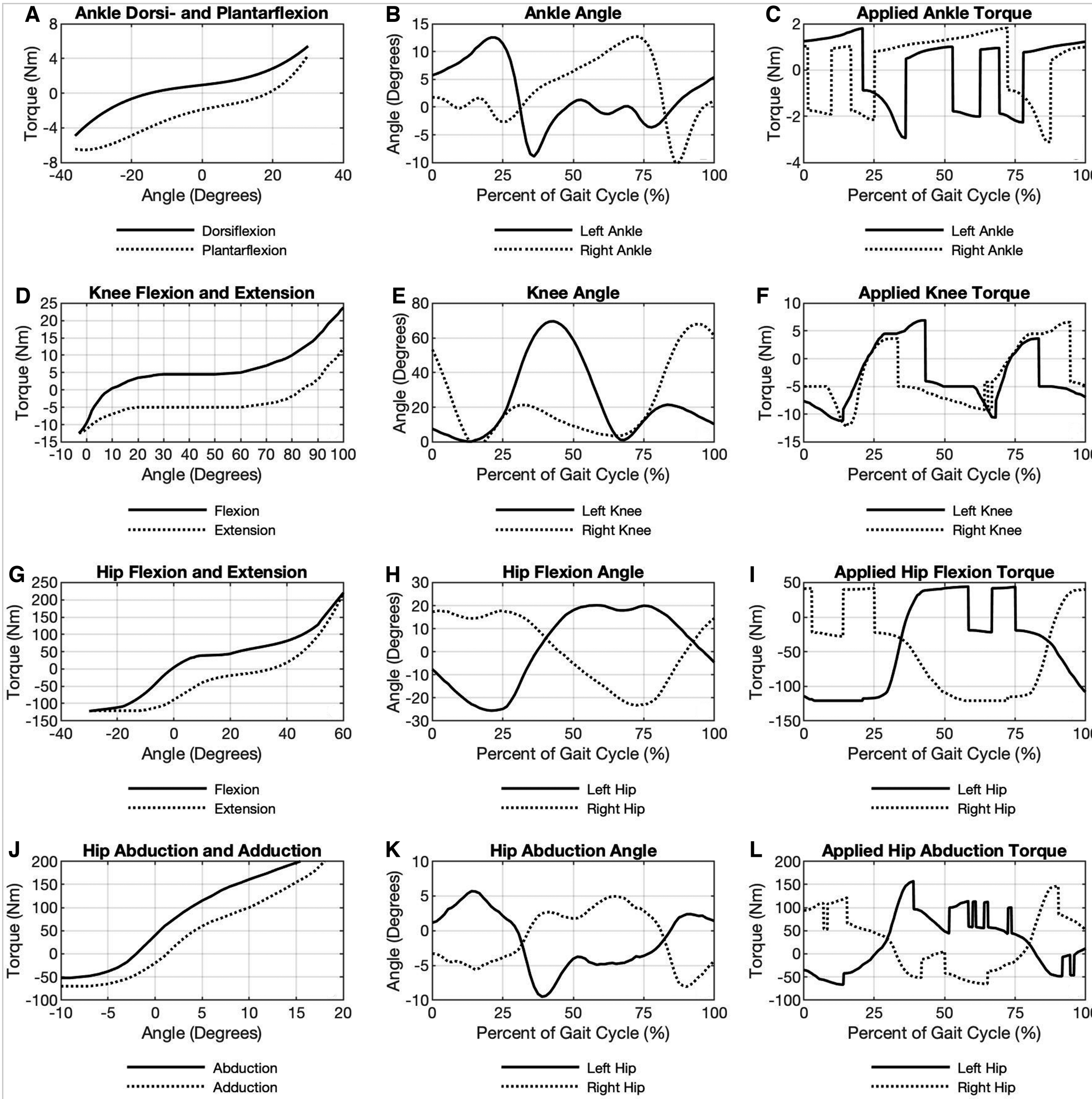

Fig. 1. Top row: A) EMU ankle joint-torque relationship (dorsiflexion/plantarflexion); B) ankle kinematics (0° represents the foot at a 90° angle from the tibia, dorsiflexion is positive); and C) associated ankle joint torques (positive torques resist dorsiflexion). Second row: D) EMU knee joint-torque relationship (flexion/extension); E) knee kinematics (0° represents the tibia parallel with the femur, flexion is positive); and F) associated knee joint torques (positive torques resist flexion). Third row: G) EMU hip flexion joint-torque relationship (flexion/extension); H) hip flexion kinematics (0° represents the femur directly below the pelvis, flexion is positive); and I) associated hip flexion joint torques (positive torques resist flexion). Bottom row: J) EMU hip abduction joint-torque relationship (abduction/adduction); K) hip abduction kinematics (0° represents the femur directly below the pelvis, abduction is positive); and L) associated hip abduction joint torques (positive torques resist abduction). Adapted from Gilkey[18] and Schmidt.[31]

reduced residual algorithm (RRA), computed muscle control (CMC), and metabolic probing. The software has proven its capability to accurately assess motions like walking[5] and running.[20]

An overview of our analysis is shown in **Fig. 2**. We used pre-existing motion capture data to simulate normal walking motion of a human musculoskeletal model. The human model is also represented in Fig. 2. From these data, we computed IK, which provides joint angles and positions during the walking motion by minimizing the squared error between experimental markers and model markers. The choice of motion capture data and, thus, the kinematics, is influential to the results of

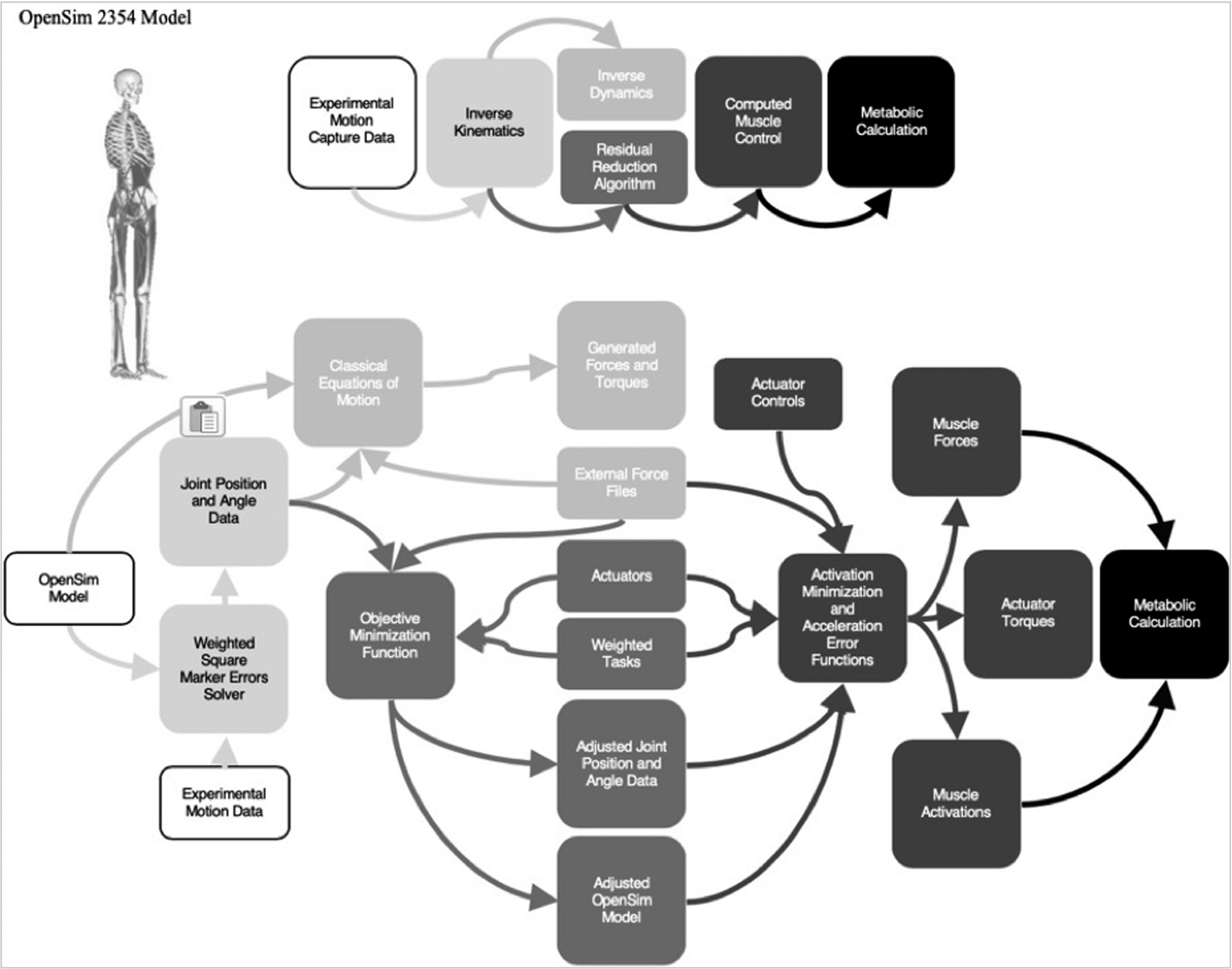

Fig. 2. The overall OpenSim methodology implemented in our musculoskeletal simulations. Experimental motion capture data refers to experimental data from tests or studies (we used already existing walking data available in OpenSim). This also determined the dimensions of the model being used. Inverse kinematics computes the joint angles and positions from the experimental motion capture data. Inverse dynamics solves for the forces and torques of the different bodies and joints in the musculoskeletal system. The human model and the inverse kinematics results are optimized and adjusted using the residual reduction algorithm to improve dynamic consistency. Individual muscle and actuator activation data, which are fed into the metabolic calculator to compute the total energy expenditure, were determined using computed muscle control. The musculoskeletal model used for the simulations is represented in the upper left corner and further details and limitations can be found in Delp et al.[11]

simulations. Slightly different kinematics may result in slightly different OpenSim solutions. Following IK, we computed joint forces and torques using ID. Briefly, ID solves for the classical equations of motion: force = mass * acceleration. Thus, the information needed to solve ID includes the musculoskeletal model, the IK results (i.e., joint angles and positions), and the external forces, which typically only include the ground reaction forces and moments, but, in the case of simulating the spacesuit, the external forces also include the EMU joint torques described above. Inverse dynamics was then performed separately with and without EMU spacesuit resistive joint torques to study the changes in joint moments due to the presence of the spacesuit.

To calculate specific muscle forces and then metabolic expenditures, we first implemented the RRA to reduce the effect of modeling and marker errors and to increase consistency with external forces. This reduction is accomplished by slightly adjusting the kinematics (joint angles root mean square, or RMS < 1°) and by altering the pelvis center of mass to minimize the objective function that accounts for activation of actuators and acceleration residuals. While similar to IK, RRA accounts for external forces and the locations of muscles and actuators when adjusting joint positions and angles. Without the adjustment, residual forces and moments might be elevated to maintain balance and dynamic consistency.

CMC computes muscle excitations that match the required forces and torques for a given set of kinematics and external forces. The input of the simulated robotic actuators (EMU-assisted conditions) is implemented at this point to reduce the necessary excitations from the muscles. The simulated robotic

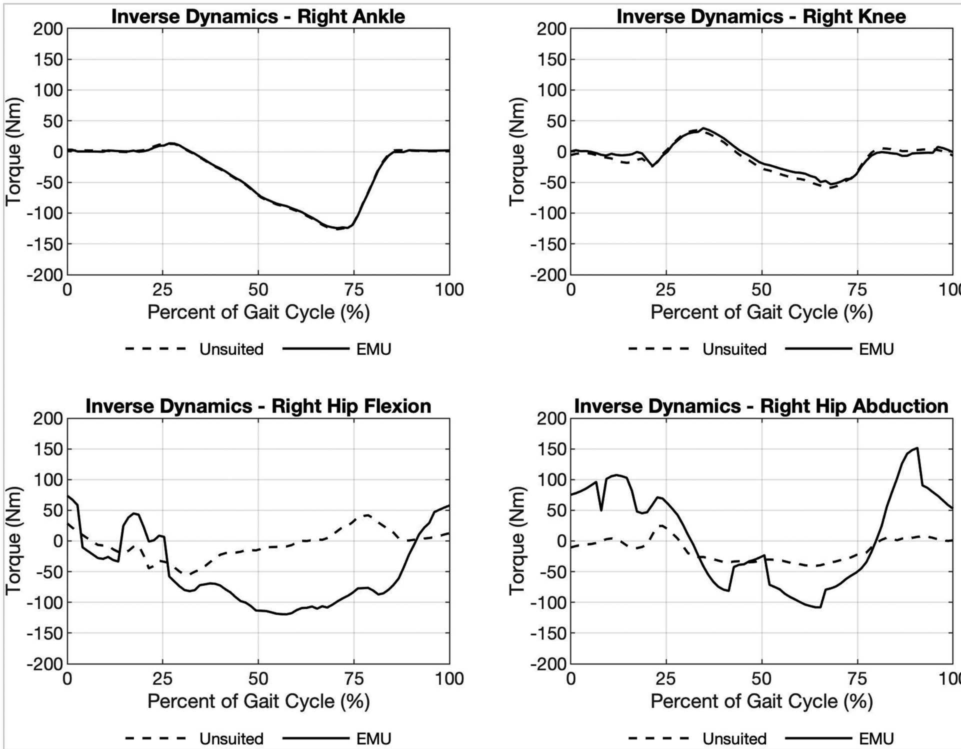

Fig. 3. Inverse dynamics results (resistive joint torques vs. percent of gait cycle) for the right ankle (dorsiflexion/plantarflexion), right knee (flexion/extension), and right hip (flexion/extension and abduction/adduction) during one gait cycle in unsuited and EMU suited conditions. Only the right side is shown.

actuators could generate a maximum joint torque of 10 Nm and were weighted such that the minimization algorithm preferred to use the assistive robotic actuators over the muscle actuators. This represents a situation where the actuators are optimized for the simulated walking gait and their activation and deactivation time are nearly instantaneous. OpenSim makes use of a closed-loop proportional-derivative (PD) controller and static optimization. First, at each time step, the forces and torques are solved for each joint. Then, a minimization algorithm calculates the contribution of muscles and actuators at each joint.

Finally, based on results from the CMC, we implemented a metabolic model developed by Umberger in 2003[33] and refined in 2010[32] to determine metabolic expenditure during our walking motion. The metabolic model captures energy change into the summation of five separate categories: basal heat rate, activation heat rate, maintenance heat rate, shortening heat rate, and mechanical work. Basal heat rate is independent of muscle movement or muscle activation and is unique from individual to individual and, thus, it was excluded from metabolic calculations. The activation and maintenance heat rates are commonly combined together because both are calculated through a purely proportional gain based on the percent of fast twitch muscle fibers and the fraction of total muscle activation. Shortening heat rate is dependent on the speed of the muscle shortening or lengthening and the efficiency of both for slow twitch and fast twitch muscle fibers. Activation, maintenance, and shortening heat rate are all dependent on if the muscle is undergoing concentric, eccentric, or isometric contraction. Lastly, mechanical work refers to the energy spent by the muscle to physically move the various bone structures (e.g., femur, shank). A more in-depth explanation of the metabolic model can be found in Umberger's 2003 publication.[33]

RESULTS

Results from ID indicate that the spacesuit increases the moment around every joint. **Fig. 3** shows the ID results for the right ankle (plantarflexion/dorsiflexion), right knee (flexion/extension), and right hip (flexion/extension and adduction/abduction) during one gait cycle in both unsuited and EMU suited conditions. Results show that the largest increases in the magnitude of the total moments occur at the hip joint for flexion/extension and abduction/adduction. Knee and ankle inverse dynamics results for the EMU suited conditions are similar to the unsuited conditions as a result of the EMU resistive joint torques being relatively small compared to the already required torques to support unsuited walking. The knee and ankle moments are influenced directly from the spacesuit resistive torques at their respective joints, but also indirectly from increase moments in other joints, such as the hip, as it helps transfer the force back to the ground. OpenSim is a useful tool to visualize and quantify the indirect effects from the other joints in spacesuits.

The metabolic calculation of the entire body during one gait cycle is shown in **Fig. 4**. The top panel shows the instantaneous

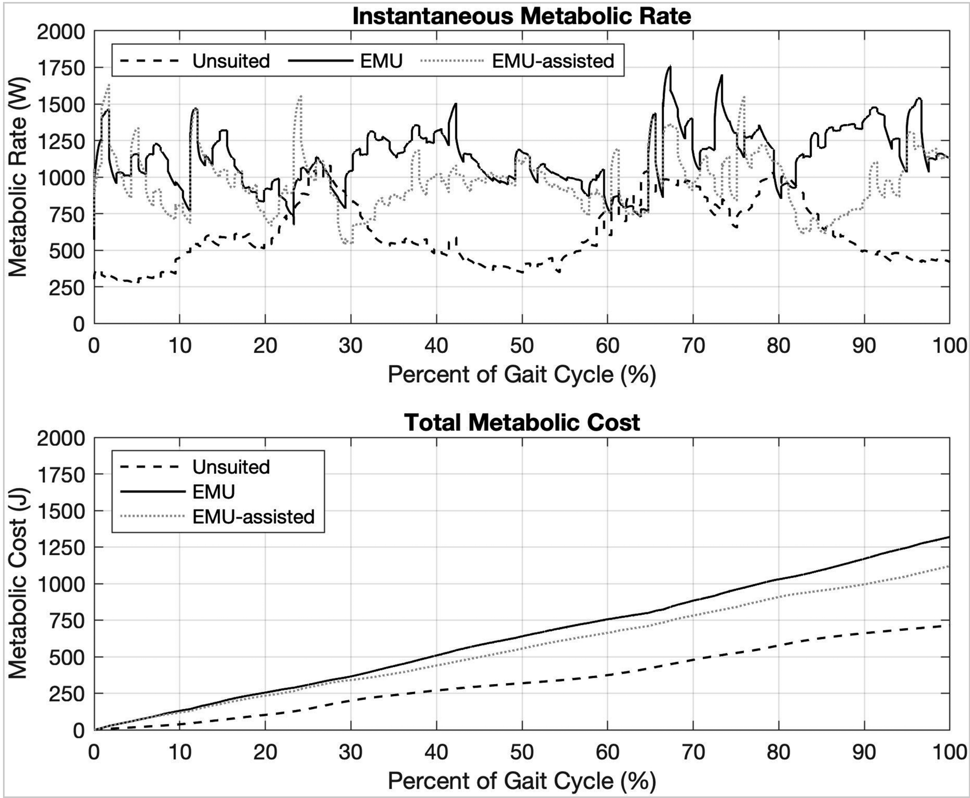

Fig. 4. Instantaneous metabolic rate (top) and total metabolic cost over time (bottom) for one gait cycle in unsuited, EMU, and EMU-assisted conditions.

Table I. Total Metabolic Cost (Per Gait Cycle and Per Time) for Unsuited, EMU, and EMU-Assisted Walking Motions.

CONDITION	J/GAIT CYCLE	kcal/GAIT CYCLE	$kcal \cdot s^{-1}$	$kcal \cdot h^{-1}$
Unsuited	713	0.170	0.142	510
EMU	1318	0.315	0.262	943
EMU-assisted	1119	0.267	0.222	799

The addition of robotic actuators improved metabolic performance by 199 J/Gait Cycle or 144 $kcal \cdot h^{-1}$.

metabolic rate (W) throughout the gait cycle while the bottom panel shows the cumulative metabolic cost (J). The total increase in metabolic consumption from an unsuited walking gait to a motion with resistive EMU torques is approximately 85%. The assistive actuators reduce the metabolic cost of the walking gait with resistive EMU joint torques by 15%.

Table I presents an overview of the metabolic cost calculated from our simulations. It shows metabolic data in terms of kilocalories needed to walk in the three simulated conditions: unsuited, EMU suited, and EMU-assisted suited conditions. The first two columns specify the energy needed during one gait cycle based on our simulations (J/Gait Cycle and kilocal/Gait Cycle; 1 kilocal = 4184 J). The third and fourth columns specify the metabolic energy as a function of time, assuming that one gait cycle is completed in 1.2 s. Thus, according to our simulations, the assistive robotics can save ~140 $kilocal \cdot h^{-1}$ (799 $kilocal \cdot h^{-1}$ vs. 943 $kilocal \cdot h^{-1}$) for a massless EMU under Earth gravitational conditions. This represents a 15% improvement in metabolic expenditure.

The individual contributions of the actuators from each joint are shown in **Table II**. For these simulations, only the actuators at the specified joint were included in the model. The second column indicates the calculated J/Gait Cycle, and the third column specifies the change in J/Gait Cycle with respect to the unassisted EMU condition. The actuators at the hip are capable of reducing the J/Gait Cycle by 177 J, which is the largest of the three joints. In comparison, the ankle and knee actuators lower the J/Gait Cycle by 94 and 117 J, respectively.

To further quantify the benefits of robotic actuation in spacesuit design, we expanded our results into a standard mission to Mars in the context of the Mars Design Reference Architecture 5.0 (DRM 5.0).[17] According to DRM 5.0, a long duration mission to Mars would result in approximately 539 d on the Martian surface. We assume an average of four weekly EVAs, which makes a total of 300 EVAs per Martian stay per crewmember. Expected "traversing distances" for these EVAs are estimated at 1–2 km per EVA before a pressurized or unpressurized rover would be used.[2]

Table II. Metabolic Cost (J/Gait Cycle) for EMU, EMU with Ankle Actuators, EMU with Knee Actuators, EMU with Hip Actuators, and EMU with All Actuators.

CONDITION	J/GAIT CYCLE	IMPROVEMENT WITH RESPECT TO EMU
EMU	1318	0
EMU-assisted (Ankle Only)	1224	94
EMU-assisted (Knee Only)	1201	117
EMU-assisted (Hip Only)	1141	177
EMU-assisted (All Joints)	1119	199

The ankle, knee, and hip actuators reduced the metabolic cost by 94, 117, and 177 J, respectively.

Thus, we could also assume that in each EVA, crewmembers walk at least 2 km to get to/from the target EVA site plus some additional walking on the actual site, which we estimate an additional 2 h walking. Assuming a gait cycle that last 1.2 s and traverses 1.4 m, we can estimate the total walking time during an EVA to be approximately 2.44 h (equivalent to 2 h 26 min; 2000 m * 1.2 s/Gait Cycle * (1/1.4 m/Gait Cycle) = 26 min plus 2 additional hours walking on site). Based on the metabolic energy expenditure shown in Table I, the SmartSuit would save one crewmember ~351.4 kilocal per EVA and ~100,000 kilocal on an 18-mo expedition to Mars (943–799 kilocal $\cdot$ h^{-1} * 2.44 h/EVA * 300 EVAs = 105,408 kilocal). Assuming 1 kg of food provides an astronaut a daily serving of 3000 kilocal, this results in a saving of approximately 33 kg of food per astronaut.

DISCUSSION

The hip joints account for approximately 80% of the metabolic reduction in our simulation. The knee and ankle actuators account for the remaining 20%. In this specific walking motion, the resistive EMU torques at the knee and ankle joints are small compared to the hip's flexion/extension and abduction/adduction resistive joint torques. The soft-robotic actuators, which can produce up to 10 Nm, are capable of overcoming the resistive spacesuit torques applied to the ankles and knees in addition to the already existing moments generated during normal walking, but the robotic actuator torques are an order of magnitude smaller than the resistive spacesuit joint torques present in the hips. Thus, the maximum benefit from the soft-robotic actuators is achieved at the hip, where there is a larger potential for minimizing the total metabolic cost.

Our model indicates that the metabolic cost of EVA traverses benefits from the use of robotic actuators. There are some instances where the instantaneous EMU-assisted metabolic rate is larger than the instantaneous EMU metabolic rate (e.g., approximately at 25% and 75% percent of the gait cycle). These represent local solutions of the optimization process within the muscle control solver, which attempts to minimize total muscle activation. Despite these instances, the overall EMU-assisted metabolic cost during a gait cycle remains lower than the EMU condition. The improvement from EMU conditions to EMU-assisted conditions is consistent with literature for exosuits in unhindered human walking. Since 2013, 12 exoskeletons have shown improvements in metabolic expenditure ranging from 3.3 to 19.8% during walking as shown by Sawicki.[30] Our suited motion improvement of 15% is on the upper range of the actuators. The hip joints benefitted the greatest from robotic actuation, which is consistent with the actuators described by Sawicki, where five of the seven actuators that most improved metabolic cost were located at the hip. The majority of exosuits reported by Sawicki were all single joint systems (while our simulation consisted of four joint actuators with a maximum of 10 Nm of torque), which limits the overall reduction of metabolic cost.

Our simulation framework can be compared to experimental results from Earth-based exosuit spacesuit analogs. Carr created an exosuit to simulate the resistive knee joint torques of the EMU spacesuit and characterized the performance of the subjects by using metabolic expenditure (W $\cdot$ kg^{-1}) and cost of transportation [J/(kg*m)].[9] The nondimensionalized Froude number (Fr) was used to normalize the movement speed between subjects. Our results showed some similarities with Carr's results. The metabolic rate for a simulation where we only included the knee joint torque was approximately 8.5 W $\cdot$ kg^{-1} compared to Carr's subjects, who ranged from 5 to 7.5 W $\cdot$ kg^{-1}. Cost of transportation was approximately 7 J/(kg*m) for the knee torque only simulation and the subjects for the spacesuit analog recorded a range closer to 4 J/(kg*m). The similarity of Carr's and the present simulation's results supports the likelihood of accuracy. The slight differences found may be the result of several factors. First, our simulation was conducted at a Fr of approximately Fr = 0.15, whereas Carr's subjects had a Fr = 0.25. In addition, our modeled subject has a mass of 75 kg, which is 2 standard deviations higher than Carr's test subjects. While the performance metrics were normalized by mass, a relationship exists between mass distribution and the metabolic cost of walking,[16] and our model's mass is concentrated in the lower body due to not having arms. When all resistive joint torques were included in the simulation (ankles, knees, and hips) the metabolic expenditure was 14.2 W $\cdot$ kg^{-1} and the cost of transportation was 11.7 J/(kg*m). Both metrics were higher than the simulation with only knee torques and also Carr's spacesuit analog, most likely due to the additional resistive joint torques at the hips and ankles.

These findings may be somewhat limited by differences between our simulations and realistic planetary conditions in altered gravity environments. For example, the walking motion used for the simulation may not be optimized for walking in a spacesuit with actuators at a fraction of Earth's gravity. In an attempt to further investigate these potential differences, we build on the dynamic similarity hypothesis, which suggests that humans have similar walking gaits when normalized by the Froude number:[1]

$$Fr = \frac{v^2}{gL}$$

where v is velocity, g is the gravity level, and L is the leg length of the individual. In our simulation, the modeled individual walks at approximately $1.16\ m \cdot s^{-1}$ at Earth gravity with a leg length of approximately 0.9 m, which yields a Froude number of Fr = 0.15. At Earth gravity, walking is most efficient at Fr = 0.25[29] and the walk-to-run transition typically takes place at Fr = 0.5.[6] In a Martian gravity field (approximately 3/8 of that on Earth), the Froud number for our simulation becomes Fr = 0.41. This is close to the predicted walk-to-run transition speed for Earth gravity. However, ambulation studies in Martian hypogravity simulators indicate that the walk-to-run transition would occur at approximately Fr = 0.6.[9,22] Thus, our Martian Froude number of Fr = 0.41 is considerably lower than the expected walk-to-run transition speed on Mars, supporting the idea that astronauts will still prefer to walk under these conditions. In contrast, analyses of ambulation motions and Froude numbers from the Lunar Apollo missions indicate that astronauts utilized walking, running, and loping (skipping without the support-foot exchange) at Froude numbers similar to our simulations at Martian gravity (~Fr = 0.4).[7] The A7LB spacesuit used for the Apollo missions had limited range of motion in the hips for flexion and extension and movement was difficult due to the pressure and design of the suit.[21] The high resistance to hip mobility, whether from joint torque resistance or suit design, may have been a leading cause for Apollo astronauts to adopt a loping gait as opposed to a slower walking gait. Our simulation and the benefits of robotic actuation could be extrapolated to a Martian mission, but a walking gait may not be the most frequent mode of transportation.

An additional limitation is the assumption of a massless spacesuit. The weight of a spacesuit could affect the metabolic cost of ambulation in several ways. First, additional loading increases metabolic cost at any gravity condition.[19] Also, the additional mass creates a distributed load on the astronaut, which may impact the efficiency of the ambulatory movement.[16] In contrast, internal pressures, even if they contribute to the resistive joint torques, also partially offload the suit from the astronaut.[7] This reduces the load-carrying cost of the spacesuit, but they do so at the cost of joint mobility, which in turn increases metabolic expenditure. We hypothesize that the inclusion of mass increases the overall metabolic cost during walking and that the benefit of incorporating robotic actuation remains of a similar magnitude, but further research is needed to accurately quantify the relationship between spacesuit mass and metabolic cost during ambulation.

We conducted additional simulations to further investigate potential differences between the EMU and Mark III spacesuits. Since hip angle-torque relationships are not available for the Mark III, we compared the EMU and Mark III including resistive spacesuit knee and ankle joint torques only. The EMU simulation resulted in a metabolic cost per gait cycle of 797 kilocal compared to the Mark III simulation, which resulted in 790 kilocal per gait cycle. These results indicate that, while the Mark III suit was designed for planetary EVAs, the required knee and ankle torques appear to be very similar to those required when wearing the EMU, at least for the walking motion being investigated. Based on these results, we expect that the Mark III improvements in mobility are mostly related to the hip joint.

An advantage of our framework is the flexibility to incorporate new walking gaits and gravity levels as motion data (both suited data and data in partial gravity environments) becomes available. Building on previous work on spacesuit simulators, hip EMU joint torque data was conservatively extrapolated to cover the entire range of motion present in the specific walking motion analyzed. In the future, joint torque and gait data related to the newly developed Exploration EMU planetary spacesuit could easily be integrated in our computational framework to generate more accurate predictions of future planetary traverses on the Moon. Despite the limitations, our musculoskeletal framework contributes to quantifying the impact of resistive spacesuit joint torques and robotic actuation on human performance, providing new insights into human-spacesuit interaction, musculoskeletal performance, and metabolic expenditures during planetary EVA exploration.

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