Computational Prediction of Muscle Moments During ARED Squat Exercise on the International Space Station

Benjamin J. Fregly[1]
Department of Mechanical and
Aerospace Engineering,
University of Florida,
231 MAE-A Building,
P.O. Box 116250,
Gainesville, FL 32611
e-mail: fregly@ufl.edu

Christopher D. Fregly
International Baccalaureate Program,
Eastside High School,
1201 Southeast 43rd Street,
Gainesville, FL 32641
e-mail: dfregly@gmail.com

Brandon T. Kim
International Baccalaureate Program,
Eastside High School,
1201 Southeast 43rd Street,
Gainesville, FL 32641
e-mail: kimbrandontae@gmail.com

Prevention of muscle atrophy caused by reduced mechanical loading in microgravity conditions remains a challenge for long-duration spaceflight. To combat leg muscle atrophy, astronauts on the International Space Station (ISS) often perform squat exercise using the Advanced Resistive Exercise Device (ARED). While the ARED is effective at building muscle strength and volume on Earth, NASA researchers do not know how closely ARED squat exercise on the ISS replicates Earth-level squat muscle moments, or how small variations in exercise form affect muscle loading. This study used dynamic simulations of ARED squat exercise on the ISS to address these two questions. A multibody dynamic model of the complete astronaut-ARED system was constructed in OpenSim. With the ARED base locked to ground and gravity set to 9.81 m/s^2, we validated the model by reproducing muscle moments, ground reaction forces, and foot center of pressure (CoP) positions for ARED squat exercise on Earth. With the ARED base free to move relative to the ISS and gravity set to zero, we then used the validated model to simulate ARED squat exercise on the ISS for a reference squat motion and eight altered squat motions involving changes in anterior–posterior (AP) foot or CoP position on the ARED footplate. The reference squat motion closely reproduced Earth-level muscle moments for all joints except the ankle. For the altered squat motions, changing the foot position was more effective at altering muscle moments than was changing the CoP position. All CoP adjustments introduced an undesirable shear foot reaction force that could cause the feet to slip on the ARED footplate, while some foot and CoP adjustments introduced an undesirable sagittal plane foot reaction moment that would cause the astronaut to rotate off the ARED footplate without the use of some type of foot fixation. Our results provide potentially useful information for achieving desired increases or decreases in specific muscle moments during ARED squat exercise performed on the ISS.

[DOI: 10.1115/1.4031795]

Keywords: dynamic simulation, moment prediction, muscle loading, space exploration, microgravity, biomechanics

Introduction

NASA is planning to return human beings to the Moon by the year 2020 as a stepping stone for a subsequent manned mission to Mars [1]. However, how to maintain muscle mass in microgravity conditions remains a technological challenge [2–5]. For any activity, reduced gravity leads to reduced mechanical loading on muscles, which in turn can lead to reduced muscle mass (i.e., atrophy). Muscle atrophy could hinder an astronaut's ability to complete mission-critical tasks, could put an astronaut at increased risk of muscle strain injuries while performing those tasks, and could limit normal function upon return to Earth [2].

Because maintenance of muscle mass is such a critical issue, NASA researchers have developed a number of specialized exercise devices for long-duration spaceflight [3]. One of those devices, the ARED, is currently in use on the ISS [6]. The ARED allows astronauts to perform a wide variety of high resistance exercises, including parallel squat exercise for maintaining leg muscle mass. To minimize force transmission to the ISS during exercise, the ARED can rotate and translate relative to the ISS via a vibration isolation system (VIS). During squat exercise, the astronaut holds the ARED shoulder bar across the shoulders while standing on the ARED footplate. Two vacuum cylinders then apply a compressive load to the astronaut between the shoulder bar and the footplate. Vacuum cylinder loads are typically set to an Earth-level value plus 70% of body weight (BW) to account for the lack of gravity.

Though the ARED has been shown to be as effective as free weights for building muscle strength and volume on Earth [6], the extent to which ARED squat exercise on the ISS achieves Earth-equivalent back and leg muscle moments remains unknown [7]. It is also unknown how small variations in the way ARED squat exercise is performed would affect muscle moments. The primary reason is that the necessary experimental equipment is not currently available on the ISS [3]. Without this equipment, the experimental data needed to estimate joint moments via inverse dynamics cannot be obtained [8]. While raw video of squat exercise on the ISS could be used to estimate astronaut and ARED joint motions, no options currently exist for estimating foot reaction forces during ARED squat exercise. Thus, an alternate approach—such as one that uses computational simulations [8,9]—is needed to estimate how well back and leg muscle moments produced by ARED squat exercise on the ISS replicate muscle moments produced by ARED squat exercise on Earth.

This study utilized computational simulations to estimate back and leg muscle moments experienced by astronauts during ARED

---

[1] Corresponding author.

Manuscript received May 10, 2015; final manuscript received October 4, 2015; published online October 30, 2015. Assoc. Editor: Silvia Blemker.

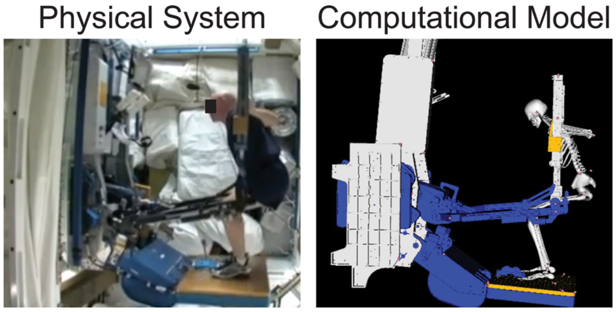

Fig. 1 Picture of an astronaut performing ARED squat exercise on the ISS [11] (left) and picture of the complete astronaut-ARED model in the same configuration (right)

squat exercise on the ISS. The two questions to be answered were the following: (1) How closely does ARED squat exercise on the ISS using a 70% BW replacement load replicate Earth-level back and leg muscle moments? (2) How much, and in what way, would two simple foot-related adjustments (a change in AP foot position or CoP position on the ARED footplate) alter back and leg muscle moments during ARED squat exercise on the ISS? To answer these questions, we developed a three-dimensional multibody dynamic model of the complete astronaut-ARED system in OpenSim [10] and used it to simulate ARED squat exercise on both Earth and the ISS. Inputs to the model were sagittal plane joint motions of the human body (back, hips, knees, and ankles), while outputs were sagittal plane muscle moments, sagittal plane motion of the ARED, out-of-plane motion of the human body joints, and shoulder and foot reaction forces (including foot CoP positions) produced by the exercise. Experimental data were used to define two reference ARED squat motions, one for a human subject on Earth, and one for an astronaut on the ISS. To validate the model, we first used the reference squat motion from Earth as model inputs and showed that model outputs closely reproduced Earth-based experimental ground reactions and muscle moments. To address our two main questions with the validated model, we then used the reference squat motion from the ISS, modified as necessary to account for the two foot-related adjustments, as model inputs and predicted the same model outputs on the ISS. Our results provide insight into the likely effectiveness of ARED squat exercise for maintaining leg muscle mass on the ISS and into how simple foot-related adjustments might alter the distribution of leg and back muscle moments.

Methods

Computational Model Development. To perform our proposed study, we constructed a three-dimensional multibody dynamic model of the complete astronaut-ARED system in OpenSim (Fig. 1, see Appendix). Modeling the entire system was necessary so that joint moments produced by the astronaut's leg and back muscles could be predicted without the use of ground reaction force data, which are currently not available for ARED squat exercise on the ISS. The model combined three-dimensional computer-aided design (CAD) geometry of ARED machine components obtained from the NASA Glenn Space Center with a published three-dimensional full-body OpenSim skeletal model available online [12].[2]

We modified the kinematic structure of the published OpenSim skeletal model so that it would work within the framework of the combined astronaut-ARED model. The model initially possessed 37 degrees-of-freedom (DOFs). We locked all upper-body joints and both toe joints in positions consistent with a squat motion, leaving 21 DOFs. We then changed the joint structure of the model by replacing the 6 DOF ground-to-pelvis joint with a 6 DOF ground-to-shoulders joint. This change allowed OpenSim to calculate inverse dynamic loads at the shoulders rather than the pelvis using a bottom-up approach. The remaining joints included a lower back and both hips modeled as ball-and-socket joints, both knees modeled as pin joints, and both ankles modeled as two nonintersecting pin joints.

Once the full-body OpenSim skeletal model was modified, we defined the kinematic structure of the ARED and how the skeletal model integrated with it. The ARED kinematic structure was modeled entirely in the sagittal plane. The VIS connecting the ARED to the ISS was modeled using a single 3 DOF planar joint, with each axis controlled by a passive spring–damper. All remaining ARED joints were modeled as unactuated pin joints. Where two pin joints along the same medial–lateral axis existed in the actual ARED, only a single pin joint located at the midline of the device was used in the model. The shoulders of the skeletal model were connected to the ARED shoulder bar via a 3 DOF planar joint with the two translations locked to permit calculation of two reaction forces. Each foot of the skeletal model was connected to the ARED footplate via a weld constraint that permitted calculation of six reaction quantities (three forces and three torques) with respect to the heel of each foot.

The kinematic structure of the resulting model included two closed kinematic chains. Excluding the VIS, the astronaut-ARED system essentially formed a seven-link closed kinematic chain possessing four DOFs in the sagittal plane. A closed chain in the frontal plane also existed involving the ARED footplate and the lower body and pelvis of the skeletal model, making the reaction forces redundant in the two weld constraints between the feet and ARED footplate. However, since OpenSim automatically splits redundant reaction forces in weld constraints, identical reaction forces were generated by the model between each foot and the ARED footplate.

We used the resulting astronaut-ARED model to develop a hybrid approach for simulating ARED squat exercise on Earth or the ISS. The approach was a "hybrid" in that it combined forward and inverse dynamic simulation methods. Specifically, the sagittal plane joint motions of the human body (back, hips, knees, and ankles) were prescribed as time-varying inputs to each simulation, while the sagittal plane motion of the ARED, the out-of-plane motion of the body, the shoulder and foot reaction forces (including foot CoP positions), and the sagittal plane muscle moments (back, hips, knees, and ankles) produced by the body were predicted as time-varying outputs (i.e., simultaneous forward and inverse dynamic solutions for different parts of the model). Sagittal plane joint motion inputs were the same for both legs, completely defining the kinematics of the effective seven-link closed kinematic chain and ensuring that the out-of-plane motions of the hips and ankles would always be symmetric. Muscle moment outputs (i.e., the net moments produced by muscles spanning each joint) were treated as an indicator of the magnitude of the muscle forces required to produce a given squat motion. Additional simulation inputs were constant model parameter values, including the value of gravitational acceleration, the value of the two vacuum cylinder loads (assumed to be equal and constant), the AP position of the feet on the ARED footplate, and the initial positions and velocities of the VIS DOFs (ISS simulations only). To implement the hybrid solution approach in OpenSim, we used an OpenSim forward dynamic simulation since an OpenSim inverse dynamic analysis would require that the motion of all DOFs in the model be prescribed, which would produce unrealistic nonzero moments at unactuated ARED joints.

Experimental Data Analysis. We used experimental movement data to define a reference ARED squat motion on Earth and on the ISS. For the Earth-based reference motion, we obtained experimental data previously collected from a male subject (height 1.75 m, mass 76 kg) who performed ARED squat exercise at NASA Johnson Space Center [13]. Institutional review board approval and subject informed consent were obtained prior to

---

[2] https://Simtk.org

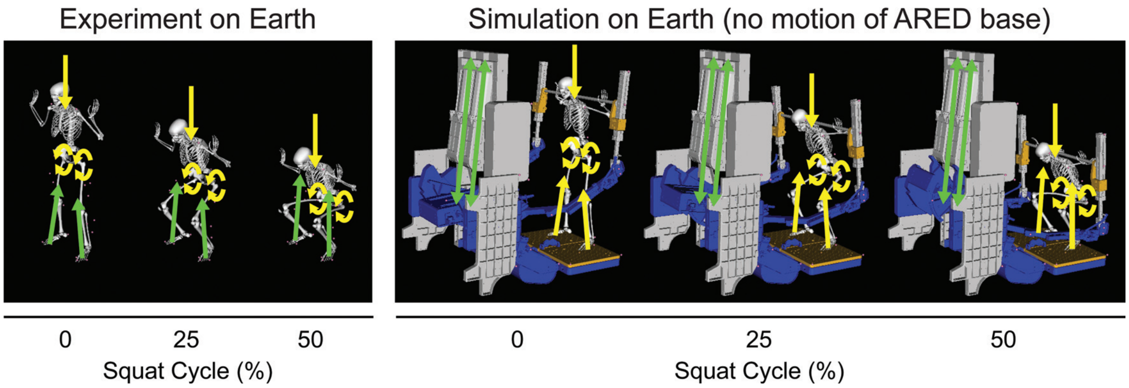

Fig. 2 Experimental determination of muscle moments and foot and shoulder forces during ARED squat exercise on Earth (left) and computational simulation of the same quantities on Earth (right). Gravity was set to 9.81 m/s^2 and the ARED base was locked to ground. For the experiment, measured foot reaction forces (green arrows) were inputs to an OpenSim skeletal model, while muscle moments and shoulder force (yellow arrows) were outputs calculated via an inverse dynamic approach. For the simulation, calibrated ARED vacuum cylinder loads (green arrows) were inputs to a complete astronaut-ARED OpenSim model, while muscle moments, shoulder force, and foot reaction force (yellow arrows) were outputs calculated via a hybrid forward-inverse dynamic approach. Arrows are only for graphical representation of the various input and output quantities. Muscle moment arrows for joints other than the hips have been omitted for clarity.

testing. Data included surface marker positions measured by a 12-camera motion capture system (BTS Bioengineering S.p.A., Milan, Italy) and ground reaction forces and moments measured by two force plates (Model 9261, Kistler Instruments AG, Winterthur, Switzerland). Surface markers were placed over the lower back (sacrum) and the right and left shoulders (acromiums), approximate hip centers (greater trochanters), approximate knee centers (lateral epicondyles), approximate ankle centers (lateral malleoli), heels, and toe tips. Force platforms were placed side-by-side on the ARED footplate to allow independent measurements for each foot. The ARED vacuum cylinder loads were selected based on the maximum load for which the subject could perform 12 repetitions [14], which is indicative of 70–75% of the subject's one repetition maximum [15]. One representative cycle of squat data was selected for analysis, where a cycle was defined to be from the most extended to the most flexed posture and back to the most extended posture.

We used OpenSim to analyze the selected cycle of surface marker and ground reaction data and generate a reference squat motion for Earth, including reference muscle moments. First, we performed a model scaling analysis that used static trial marker data to scale the skeletal portion of our OpenSim model. Next, we performed an inverse kinematic analysis that used the scaled skeletal model and dynamic marker data to determine the subject's joint motions over the squat cycle. Finally, we performed an inverse dynamic analysis that used the scaled skeletal model, joint motions from inverse kinematics, and ground reactions measured experimentally to estimate the corresponding muscle moments and shoulder forces. These quantities were needed for subsequent evaluation of the complete astronaut-ARED model. For each moment and force, the largest value near the middle of the squat cycle was selected for analysis. In addition, we calculated AP CoP position relative to the heel from the experimental ground reaction data for each foot. Results from the right and left legs were averaged based on symmetry. The ARED portion of the OpenSim model was not used for any of these tasks.

For the ISS-based reference motion, we analyzed a NASA YouTube video of a male astronaut (height 1.68 m, mass 75 kg) performing ARED squat exercise on the ISS [11] (Fig. 1). The video provided a sagittal plane view of the astronaut and the entire ARED moving with respect to the ISS. We selected key identifiable landmarks on the astronaut and ARED for manual digitization. We then used DLTdv5 [16], a freely available video digitization program for MATLAB, to digitize the two-dimensional locations of the landmarks over one complete squat cycle. We scaled the digitized points by the known dimensions of two ARED components to convert the resulting point motion data into units of meters.

Similar to the Earth situation, we used OpenSim to analyze the measured point motion data and generate a reference squat motion for the ISS. First, we performed a model scaling analysis that used the known height of the astronaut and the average distances between digitized points defining segments lengths to scale the skeletal portion of our OpenSim model. Next, we added markers to the complete astronaut-ARED model in locations corresponding to the digitized points, and we offset the model markers in the lateral direction to a common sagittal plane to facilitate alignment with the two-dimensional digitized point locations. We also adjusted the AP location of the feet on the ARED footplate to reflect the placement used on the ISS. Finally, we performed an inverse kinematic analysis that used the complete astronaut-ARED model and the digitized points to determine the astronaut's joint motions within the ARED and ARED motion relative to the ISS. Unlike for the Earth situation, the complete model was used to perform the inverse kinematic analysis due to motion of the ARED relative to the ISS, and no muscle moments or shoulder forces could be calculated using only the skeletal portion of the model due to the lack of foot reaction force data on the ISS.

Reference Motion Simulation on Earth. We evaluated the complete model's ability to predict muscle moments, foot reaction forces, AP CoP positions, and shoulder reaction forces accurately by comparing simulation and experimental results for ARED squat exercise on Earth (Fig. 2). Simulation results were generated by performing an OpenSim forward dynamic simulation as described above using the complete astronaut-ARED model, where the skeletal portion of the model was scaled to be consistent with the subject on Earth. Sagittal plane motion inputs for the back, hips, knees, and ankles were taken from the Earth-based reference motion, gravitational acceleration was set to 9.81 m/s^2, and the 3 DOFs in the VIS were locked to prevent ARED motion relative to ground. No ground reaction force data were input since the complete model predicts these data. Foot positions on the ARED footplate and vacuum cylinder loads used in the Earth-based experiments were not available from NASA. Consequently, we made manual adjustments to the AP position of the feet on the ARED footplate and the magnitude of the vacuum cylinder loads until the simulation produced the best match (i.e., minimum sum of squares of errors) with experimental ground reaction forces and shoulder forces.

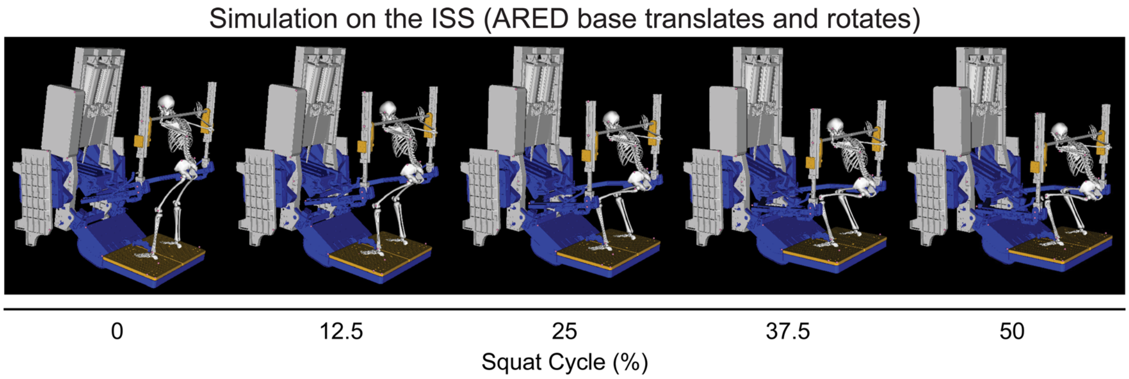

Fig. 3 Motion sequence for computational simulation of muscle moments and foot and shoulder forces during ARED squat exercise on the ISS. Gravity was set to zero and the ARED base was free to translate and rotate relative to the ISS through the VIS.

Reference Motion Simulation on the ISS. We also used the complete model to predict muscle moments, foot reaction forces, AP CoP positions, and shoulder reaction forces for ARED squat exercise on the ISS so that the simulation results could be compared with experimental results for ARED squat exercise on Earth (Fig. 3). Simulation results were again generated by performing an OpenSim forward dynamic simulation using the complete astronaut-ARED model, where the skeletal portion of the model was scaled to be consistent with the astronaut on the ISS. Sagittal plane motion inputs for the back, hips, knees, and ankles were taken from the ISS-based reference motion, gravitational acceleration was set to $0\,\mathrm{m/s^2}$, and the 3 DOFs in the VIS were unlocked to allow ARED motion relative to the ISS. For the VIS DOFs, the spring–damper parameter values and initial conditions were selected to reproduce motion on the ISS. The load in the two vacuum cylinders was set to the Earth-level value plus a 70% BW replacement load. Simulation predictions were compared with Earth-based experimental results to estimate how closely ARED squat exercise on the ISS reproduces Earth-level muscle, foot, and shoulder loads.

Altered Motion Simulations on the ISS. In addition, we simulated eight altered ARED squat motions on the ISS to investigate whether two simple foot-related adjustments could produce large changes in muscle moments. The two adjustments were: (1) an AP shift in the average CoP position (±15 cm) while keeping the foot position the same on the ARED footplate, and (2) an AP shift in foot position (±15 cm) while keeping the average CoP position the same on the ARED footplate (Table 1). Since the skeletal portion of the model functioned within a closed kinematic chain, simulating these two foot-related adjustments required altering the reference squat motion for the ISS.

To generate altered input motions for any given foot position, we developed an analytical optimization procedure. The procedure assumed that for a given foot position on the ARED footplate, the desired average AP CoP position was achieved by keeping the reference knee and back motions the same and offsetting the reference ankle and hip motions by the smallest constant amounts possible. We made these assumptions since knee motion defines squat depth, which we wanted to keep the same, and since lumbar bending was minimal and nearly identical for the reference squat motions on Earth and the ISS. For each altered motion condition, we first moved the feet to the desired AP position on the ARED footplate. We then performed an initial simulation using the reference squat motion for the ISS to determine the corresponding average AP CoP position. We next approximated the desired CoP position as a linear function of the unknown ankle and hip angle offsets using a two-variable first-order Taylor series expansion

$$f(y,z) = f(0,0) + \frac{\partial f(0,0)}{\partial y} y + \frac{\partial f(0,0)}{\partial z} z \tag{1}$$

In this equation, y is the unknown ankle angle offset, z is the unknown hip angle offset, $f(0,0)$ is the average AP CoP position given by the initial simulation with both offsets set to zero, $f(y,z)$ is the desired average AP CoP position to be achieved by the smallest possible offsets y and z, and the two partial derivatives $\partial f(0,0)/\partial y$ and $\partial f(0,0)/\partial z$ are found using finite differencing methods. Rearranging Eq. (1) produced one linear equation in the two unknown offsets y and z

$$\frac{\partial f(0,0)}{\partial y} y + \frac{\partial f(0,0)}{\partial z} z = f(y,z) - f(0,0)$$

$$\underbrace{\begin{bmatrix} \dfrac{\partial f(0,0)}{\partial y} & \dfrac{\partial f(0,0)}{\partial z} \end{bmatrix}}_{A} \underbrace{\begin{bmatrix} y \\ z \end{bmatrix}}_{x} = \underbrace{\begin{bmatrix} f(y,z) - f(0,0) \end{bmatrix}}_{b} \tag{2}$$

The underdetermined linear equation $Ax = b$ in Eq. (2) was solved in MATLAB for the two unknown angle offsets using the matrix pseudo inverse, which provided the minimum magnitude solution

$$x = \mathrm{pinv}(A) * b \tag{3}$$

After offsetting the ankle and hip motion curves by the calculated values, we performed a final simulation to calculate the resulting ground reaction forces, muscle moments, and shoulder forces and to verify that the desired average AP CoP position was achieved.

Table 1 Summary of altered motion cases for simulated ARED squat exercise on the ISS. Top section (Case 1): AP adjustments in average foot CoP position using the reference foot position on the ARED footplate. Bottom section (Case 2): AP adjustments in foot position using the reference average CoP position on the ARED footplate.

Case	Position	Change (cm)				
1	CoP	−15	−7.5	0	+7.5	+15
	Foot	0	0	0	0	0
2	CoP	0	0	0	0	0
	Foot	−15	−7.5	0	+7.5	+15

Results

Reference Motion Simulation on Earth. Comparisons between Earth simulated and Earth experimental forces, moments, and CoP positions are provided in Fig. 4 and Table 2 (top). Percent root-mean-square (rms) differences between experimental and

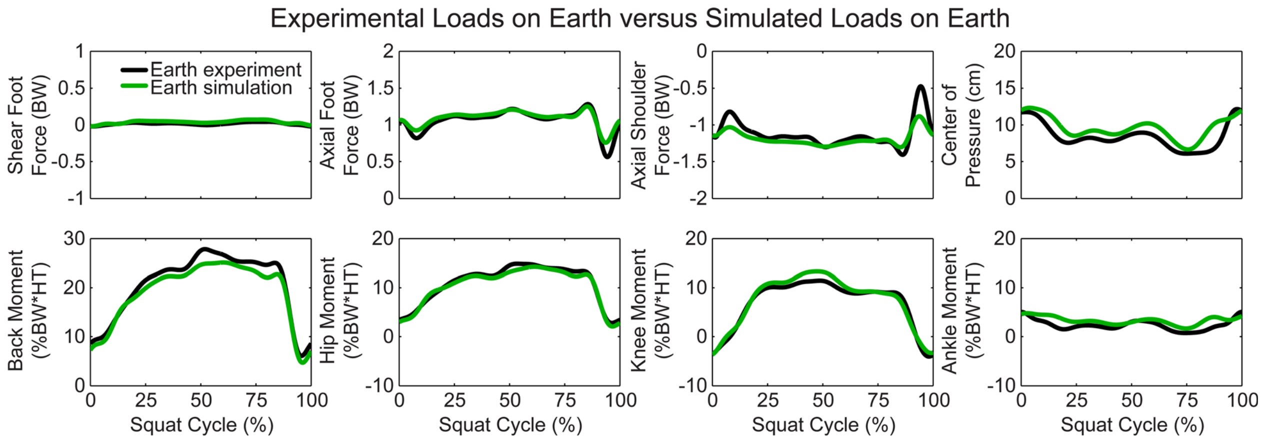

Fig. 4 Comparison of Earth experimental (black/dark) and Earth simulated (green/light) shear and axial foot forces, shoulder axial force, foot CoP relative to the heel, and back, hip, knee, and ankle moments for one cycle of ARED squat exercise. The squat cycle is defined from most extended posture to most flexed posture and back to most extended posture. Axial forces are positive in the superior direction, CoP is positive anterior to the heel position, and muscle moments are positive in the extensor direction.

Table 2 Summary of differences in forces, moments, and foot CoP between ARED squat exercise measured on Earth and simulated on Earth (top section) or the ISS (bottom section). Percent rms differences were calculated by dividing each rms difference by the largest peak experimental force, moment, or CoP value. *r* value indicates the correlation coefficient.

Simulation condition	Predicted quantity	rms difference	% rms difference	*r* value
Earth	Axial shoulder force (BW)	0.11	8.2	0.95
	Back moment (%BW × HT)	1.60	5.7	1.00
	Hip moment (%BW × HT)	0.62	2.2	0.99
	Knee moment (%BW × HT)	1.00	3.6	0.99
	Ankle moment (%BW × HT)	1.19	4.3	0.73
	Axial foot force (BW)	0.06	4.2	0.98
	Shear foot force (BW)	0.02	1.8	0.90
	CoP position (cm)	1.43	11.7	0.89
ISS	Axial shoulder force (BW)	0.78	55.1	0.68
	Back moment (%BW × HT)	3.30	11.9	0.94
	Hip moment (%BW × HT)	2.12	7.6	0.94
	Knee moment (%BW × HT)	2.00	7.2	0.96
	Ankle moment (%BW × HT)	3.31	11.9	0.72
	Axial foot force (BW)	0.15	11.0	0.75
	Shear foot force (BW)	0.04	2.7	0.01
	CoP position (cm)	4.81	39.6	0.62

simulated curves were less than or equal to 8.2% for all quantities except CoP position, which had a difference of 11.7%. Correlation coefficients (*r* values) between experimental and simulated curves were greater than or equal to 0.89 for all quantities except the ankle moment, which had a lower *r* value of 0.73 but also a smaller amplitude than the knee, hip, and back moments. The axial and shear foot reaction forces were predicted with percent rms differences being less than or equal to 4.2% and *r* values being greater than or equal to 0.90.

Reference Motion Simulation on the ISS. Comparisons between ISS simulated and Earth experimental forces, moments, and CoP positions are provided in Fig. 5 and Table 2 (bottom). Simulated muscle moments on the ISS were within a 12% rms difference of corresponding Earth-level muscle moments. Associated *r* values were greater than or equal to 0.94 except for the ankle moment, whose lower *r* value of 0.72 was accompanied by a lower moment value compared to the knee, hip, and back. Percent rms differences between Earth experimental and ISS simulated shoulder forces were greater than 55% due to the large BW replacement load on the ISS, while percent rms differences between Earth and ISS foot reaction forces were less than or equal to 11%. The CoP position was about 7 cm closer to the heel during the ISS simulation than during the Earth experiment.

Altered Motion Simulations on the ISS. Changes in simulated muscle moments and shear foot reaction force on the ISS due to AP changes in CoP and foot position are provided in Fig. 6. Changing foot position had a larger effect on peak muscle moments than did changing average CoP position. In general, moving the CoP backward (forward) produced similar direction but smaller amplitude changes in peak muscle moments as did moving the feet forward (backward). In all cases, peak knee moment changes were in the opposite direction to peak back, hip, and ankle moment changes. For altered CoP positions, the peak ankle moment changed the most, while for altered foot positions, the peak back moment changed the most. An important difference between the two foot-related adjustments was that AP foot position changes did not alter the near-zero shear foot reaction force, while AP CoP position changes caused it to increase by up to 15% in the forward or backward direction.

Discussion

This study simulated ARED squat exercise on the ISS allowing for realistic ARED motion relative to the ISS. The accuracy of our muscle moment predictions on Earth gives us confidence that our predictions on the ISS should be within about 6% rms error as

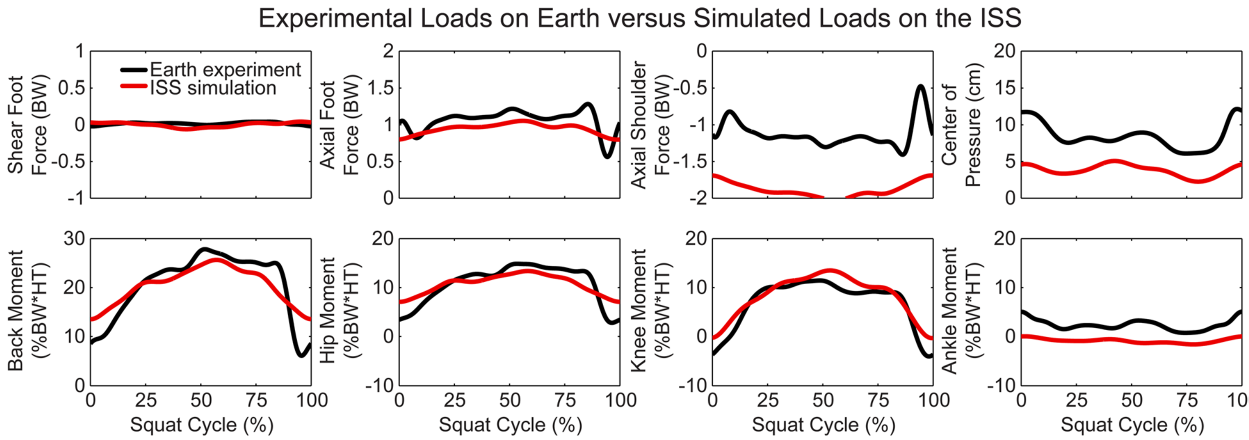

Fig. 5 Comparison of Earth experimental (black/dark) and ISS simulated (red/light) shear and axial foot forces, shoulder axial force, foot CoP relative to the heel, and back, hip, knee, and ankle moments for one cycle of ARED squat exercise. The squat cycle and positive directions are defined as in Fig. 4.

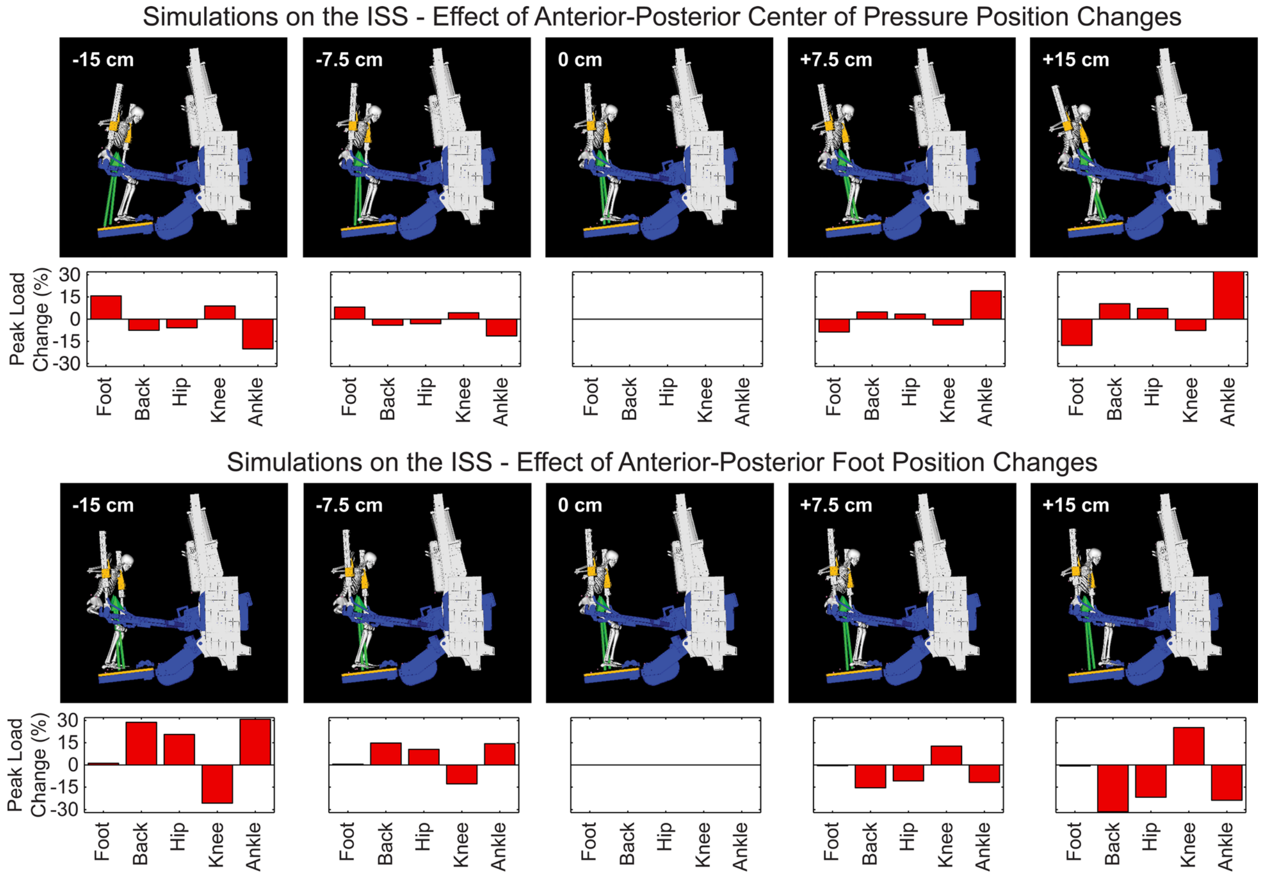

Fig. 6 Percent changes in peak normalized force and moment values for average AP CoP position adjustments (top) and AP foot position adjustments (bottom) during simulated ARED squat exercise on the ISS. Foot indicates peak shear foot force normalized by the largest peak experimental force while back, hip, knee, and ankle indicate peak muscle moments normalized by the largest peak experimental moment. CoP and foot position changes are positive in the anterior direction.

well. Overall, our simulation results suggest that ARED squat exercise on the ISS performed with a 70% BW replacement load may reproduce Earth-level muscle moments well. Increasing the gravity replacement load to 100% BW, which would be much less comfortable for astronauts [17], would likely not make muscle moments closer to those on Earth. While moving the CoP or foot position forward or backward on the ARED footplate altered muscle moments across joints in a stereotypical manner, changing the foot position would likely be the preferred approach since larger moment changes can be achieved without increasing shear forces under the feet.

Two factors help explain why a 70% BW replacement load appears to reproduce Earth-level muscle moments well but with slightly lower back and hip moments and a slightly higher knee moment. The first factor involves the normal weight distribution in the human body. On average, approximately 70% of BW is present above the hips [18]. Thus, a 70% BW replacement load would theoretically cause the hips to experience approximately the same load as on Earth, the back to experience a slightly higher load since the influence of weight from the pelvis (not experienced on Earth) is added, and the knees to experience a slightly lower load since the influence of weight from the thighs (experienced on Earth) is omitted. Indeed, when we performed an additional forward dynamic simulation where we applied the Earth-based reference motion and foot position to ARED squat exercise on the ISS, we found that the peak back moment was about 6% higher than on Earth, the peak hip moment about 3% higher, and the peak knee moment about 2% lower, consistent with the reasoning above. Thus, the normal weight distribution in the human body can explain why a 70% BW replacement load works well, but it cannot explain why the back and hip moments are slightly lower than on Earth and the knee moment slightly higher.

The second factor, which involves how ARED squat motion on the ISS differs from that on Earth, may help explain the minor muscle moment differences noted above. The astronaut modeled in our study placed his feet farther forward on the ARED footplate than did the subject tested at NASA Johnson Space Center. It is possible that astronauts on the ISS are instructed to keep their CoP far back on their heels without tilting the ARED arm bar forward or backward. The easiest way to fulfill such instructions would be to shift the feet forward on the ARED footplate, in our study by approximately 7 cm (Fig. 5, top right plot). As shown in the corresponding simulation results for altered foot positions (Fig. 6, bottom row, +7.5 cm case), such a forward shift would cause the peak back moment to decrease by about 15%, the peak hip moment to decrease by roughly 10%, and the peak knee moment to increase by around 10%. These changes are due to corresponding changes in the moment arm of the foot reaction force vector about each joint center. Combining these percent changes with the percent differences noted above resulting from a 70% BW replacement load produces total differences in peak muscle moments on the order of 9% low for the back, 7% low for the hips, and 8% high for the knees relative to ARED squat exercise on Earth. These peak moment differences are consistent with those shown in Fig. 5. It is also possible that astronauts use a more anterior foot position on the ISS simply because this position feels more comfortable in microgravity conditions, for example, due to a reduction in the back muscle moment.

The lower body joints most likely to be injured by squat exercise are the lower back and knees [19]. Our altered motion simulations suggest that both CoP and foot position adjustments could potentially modify peak back and knee muscle moments in a predictable manner. However, the simulations predicted that back and knee muscle moments would always change in opposite directions, with an increase in one moment always corresponding to a decrease in the other. For example, moving the feet forward by 15 cm would reduce the peak back moment by about 30% while raising the peak knee moment by about 25%, while moving the feet backward by 15 cm would produce the same magnitude changes but in the opposite directions. This observation is the result of how the moment arms of the foot reaction force vector relative to the back and knee joint centers change with altered CoP or foot position. Thus, if a decrease in peak back or knee moment was desired, a CoP or foot position change would need to be performed with caution, realizing that an increased muscle moment would occur at the other joint.

The altered motion simulations revealed that the AP position of the CoP and the orientation of the foot reaction force vector were determined by the orientation of the ARED arm bars (i.e., the two bars connected by the shoulder bar) relative to the ARED footplate (Fig. 6, top row). This observation can be explained by basic engineering mechanics. Consider the arm bars as a free body pinned at the bottom to the ARED “fork” and loaded at the top by a force applied by the shoulders. The moment about the pin joint must always be zero, and thus under approximate static conditions, the force acting at the top of the arm bars must be directed along the arm bars so that it exerts no moment about the bottom pin joint. Consequently, when the entire astronaut is treated as a free body, the equal and opposite force acting on the shoulders will be directed along the arm bars, and thus the foot reaction force must be directed along the arm bars as well.

Both foot-related adjustments would need to be implemented on the ISS with caution, and possibly with the addition of foot straps or some other method for maintaining foot position and orientation on the ARED footplate. In the OpenSim model, both feet were rigidly connected to the ARED footplate, and these rigid connections could generate reaction forces and moments of any magnitude necessary to prevent the feet from moving relative to the footplate. In real life on the ISS, the feet are not rigidly connected to the ARED footplate, and conditions defined by basic engineering mechanics must be satisfied so that the feet do not move. During normal squat exercise on the ISS, the foot reaction force vector remains roughly perpendicular to the ARED foot plate and the CoP remains under the feet near the heels. Consequently, no large shear forces or sagittal plane moments must be resisted at the foot-footplate interface. When the CoP position is adjusted forward or backward, the foot reaction force vector becomes tilted relative to the ARED footplate (Fig. 6, top row), introducing a shear component of foot reaction force that could cause the feet to slip on the footplate. When the CoP position is adjusted backward or the foot position is adjusted forward (Fig. 6, top left and bottom right), the CoP moves outside the base of support of the feet in the posterior direction, introducing a sagittal plane foot reaction moment that would cause the astronaut to rotate off the footplate. Both situations could potentially cause astronaut injury. While frictional forces under the feet may be sufficient to resist small shear forces, foot straps or some other foot fixation method would be needed to resist a large shear force or sagittal plane moment. If no foot fixation method was introduced, the safest adjustment would appear to be a posterior change in foot position, which does not introduce any foot shear forces and maintains the CoP under the base of support of the feet.

Our study possessed several limitations that are worthy of discussion. One limitation was that assumptions were required to generate altered squat motions on the ISS. No data are currently available describing how astronauts on the ISS perform ARED squat exercise differently for specified changes in foot or CoP position on the ARED footplate. In the absence of such data, we assumed that knee and back motions remained the same for all altered squat motions, since knee motion defines how deeply a squat is performed, and the back angle remains virtually unchanged during squat exercise. Thus, offsetting the ankle and hip motions by the smallest amounts possible seemed the most reasonable way to generate altered motion patterns. The average AP CoP positions produced by our altered squat motion simulations were within a few millimeters of the average positions predicted by our analytical optimization procedure, indicating that the relationship between average CoP position and ankle and hip angle offsets was indeed close to linear. Thus, use of an analytical optimization procedure to define the altered motion patterns did not introduce additional inaccuracies into the prediction process.

Another important limitation was modeling of different subjects performing ARED squat exercise on Earth and on the ISS, and furthermore, not having data from multiple subjects for both situations. Ideally data would have been available from the same subject on Earth and the ISS, and better yet, from multiple subjects under both conditions. Unfortunately, only one video of ARED squat exercise on the ISS with a clear sagittal plane view of the astronaut was available on YouTube, and only one data set of ARED squat exercise on Earth was available from NASA. Consequently, we were forced to analyze different subjects on Earth and on the ISS.

To evaluate how analysis of different subjects affected our assessment of ARED squat exercise on the ISS, we calculated the sensitivity of simulated muscle moments to changes in subject height and mass for both situations. To perform the sensitivity analyses, we scaled subject height and mass separately by ±1% in our astronaut-ARED OpenSim model, performed additional forward dynamic simulations for squat exercise on Earth and on the

Table 3 **Sensitivity of peak sagittal plane muscle moments to changes in subject height and mass on Earth and on the ISS. Values indicate %BW*HT change in muscle moment per 1% change in height or mass, with percent change in muscle moment relative to largest peak muscle moment shown in parentheses.**

	Earth sensitivities		ISS sensitivities	
Moment	Height	Mass	Height	Mass
Back	0.067 (0.27%)	0.19 (0.74%)	0.041 (0.16%)	0.25 (0.99%)
Hip	0.051 (0.20%)	0.10 (0.41%)	0.026 (0.10%)	0.13 (0.52%)
Knee	0.064 (0.25%)	0.060 (0.24%)	0.0072 (0.028%)	0.13 (0.50%)
Ankle	0.12 (0.47%)	0.027 (0.11%)	0.0030 (0.012%)	0.012 (0.048%)

ISS, and used finite differencing to calculate how each muscle moment would change due to a 1% change in height or mass. We found that muscle moments were relatively insensitive to changes in subject height and mass on Earth and the ISS (Table 3), as one might expect due to the use of joint moments normalized by percent BW times the height. For the height (0.07 m, or 4%) and mass (1 kg, or 1%) differences between our two subjects, worst case muscle moment changes would be less than 2% on Earth or the ISS. Thus, we do not believe that analysis of different subjects significantly affected our assessment of ARED squat exercise on the ISS.

At least two additional limitations exist for our study. The first and most significant limitation is lack of experimental foot reaction force and motion capture data from the ISS to evaluate our predicted muscle moments. NASA researchers will hopefully be able to perform a three-dimensional biomechanical analysis of ARED exercise on the ISS in the near future, and such data could allow the predictions presented in this study to be evaluated. Second, the points digitized from the NASA YouTube video [11] were less accurate than desired since the physical points did not lie in a single sagittal plane. Nonetheless, visual inspection of our reference simulation for the ISS suggested that the digitized points provided a reasonable approximation of actual astronaut and ARED motion relative to the ISS.

In conclusion, our simulation results suggest that ARED squat exercise performed on the ISS with an additional 70% BW replacement load produces muscle moments that are of comparable magnitude to those experienced on Earth. Furthermore, our altered motion simulations suggest that large changes in muscle moments can be achieved by moving the feet forward or backward on the ARED footplate while keeping the arm bars perpendicular to the footplate, though some type of foot fixation method may be needed. Our computational predictions may be helpful to NASA scientists for modifying astronaut squat exercise prescriptions to target an increase or decrease in a specific muscle moment.

Acknowledgment

This study is a compilation of Florida State Science Fair projects for the 2011–2012, 2012–2013, and 2013–2014 academic years with associated professional conference abstracts [13,20,21]. The student coauthors would like to thank Abraham Lincoln Middle School and Eastside High School in Gainesville, FL for their encouragement to pursue this project, NASA Johnson Space Center for providing ARED squat motion data on Earth, and NASA Glenn Space Center for providing ARED CAD models to perform this study.

Appendix

The OpenSim model developed for this study, sample input files for simulating ARED squat exercise on the ISS, a MATLAB plotting program, and animations of simulated motion for ARED squat exercise on Earth and on the ISS are available online.[3]

References

[1] Dickey, B., 2008, "Outposts on the Moon, Footprints on Mars: NASA's Future Exploration Plans," NASA 50th Magazine—50 Years of Exploration and Discovery, http://www.nasa.gov/50th/50th_magazine/futureExploration.html

[2] Gopalakrishnan, R., Genc, K. O., Rice, A. J., Lee, S. M. C., Evans, H. J., Maender, C. C., Ilaslan, H., and Cavanagh, P. R., 2010, "Muscle Volume, Strength, Endurance, and Exercise Loads During 6-Month Missions in Space," Aviat. Space Environ. Med., **81**(2), pp. 91–102.

[3] Genc, K. O., Gopalakrishnan, R., Kuklis, M. M., Maender, C. C., Rice, A. J., Bowersox, K. D., and Cavanagh, P. R., 2010, "Foot Forces During Exercise on the International Space Station," J. Biomech., **43**(15), pp. 3020–3027.

[4] Trappe, S., Costill, D., Gallagher, P., Creer, A., Peters, J. R., Evans, H., Riley, D. A., and Fitts, R. H., 2009, "Exercise in Space: Human Skeletal Muscle After 6 Months Aboard the International Space Station," J. Appl. Physiol., **106**(4), pp. 1159–1168.

[5] Fitts, R. H., Trappe, S. W., Costill, D. L., Gallagher, P. M., Creer, A. C., Colloton, P. A., Peters, J. R., Romatowski, J. G., Bain, J. L., and Riley, D. A., 2010, "Prolonged Space Flight-Induced Alterations in the Structure and Function of Human Skeletal Muscle Fibres," J. Physiol., **588**(Pt 18), pp. 3567–3592.

[6] Loehr, J. A., Lee, S. M. C., English, K. L., Sibonga, J., Smith, S. M., Spiering, B. A., and Hagan, R. D., 2011, "Musculoskeletal Adaptations to Training With the Advanced Resistive Exercise Device," Med. Sci. Sports Exercise, **43**(1), pp. 146–156.

[7] Davis, S. A., and Davis, B. L., 2012, "Exercise Equipment Used in Microgravity: Challenges and Opportunities," Curr. Sports Med. Rep., **11**(3), pp. 142–147.

[8] Reed, E. B., Hanson, A. M., and Cavanagh, P. R., 2015, "Optimising Muscle Parameters in Musculoskeletal Models Using Monte Carlo Simulation," Comput. Methods Biomech. Biomed. Eng., **18**(6), pp. 607–617.

[9] Ackermann, M., and van den Bogert, A. J., 2012, "Predictive Simulation of Gait at Low Gravity Reveals Skipping as the Preferred Locomotion Strategy," J. Biomech., **45**(7), pp. 1293–1298.

[10] Delp, S. L., Anderson, F. C., Arnold, A. S., Loan, P., Habib, A., John, C. T., Guendelman, E., and Thelen, D. G., 2007, "OpenSim: Open-Source Software to Create and Analyze Dynamic Simulations of Movement," IEEE Trans. Biomed. Eng., **54**(11), pp. 1940–1950.

[11] Kelly, S., 2010, "Working Out Aboard the Space Station," NASA Johnson Space Center, Houston, TX, https://www.youtube.com/watch?v=YxImeOomkUk

[12] Hamner, S. R., Seth, A., and Delp, S. L., 2010, "Muscle Contributions to Propulsion and Support During Running," J. Biomech., **43**(14), pp. 2709–2716.

[13] Fregly, C. D., Kim, B. T., Li, Z., De Witt, J. K., and Fregly, B. J., 2012, "Estimated Muscle Loads During Squat Exercise on the International Space Station," ASME Paper No. SBC2012-80785.

[14] Escamilla, R. F., Fleisig, G. S., Zheng, N., Barrentine, S. W., Wilk, K. E., and Andrews, J. R., 1998, "Biomechanics of the Knee During Closed Kinetic Chain and Open Kinetic Chain Exercises," Med. Sci. Sports Exercise, **30**(4), pp. 556–569.

[15] Mayhew, J. L., Ware, J. R., and Prinste., J. L., 1993, "Using Lift Repetitions to Predict Muscular Strength in Adolescent Males," Natl. Strength Cond. Assoc. J., **15**(6), pp. 35–38.

[16] Hedrick, T. L., 2008, "Software Techniques for Two- and Three-Dimensional Kinematic Measurements of Biological and Biomimetic Systems," Bioinspiration Biomimetics, **3**(3), p. 034001.

[17] De Witt, J. K., and Ploutz-Snyder, L. L., 2014, "Ground Reaction Forces During Treadmill Running in Microgravity," J. Biomech., **47**(10), pp. 2339–2347.

[18] Clauser, C. E., McConville, J. T., and Young, J. W., 1969, "Weight, Volume, and Center of Mass of Segments of the Human Body," Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, OH, Report No. AMRL-TR-69-70.

[19] Hartmann, H., Wirth, K., and Klusemann, M., 2013, "Analysis of the Load on the Knee Joint and Vertebral Column With Changes in Squatting Depth and Weight Load," Sport. Med., **43**(10), pp. 993–1008.

[20] Fregly, C. D., Kim, B. T., De Witt, J. K., and Fregly, B. J., 2013, "Dynamic Simulation of Muscle Loading During ARED Squat Exercise on the International Space Station," ASME Paper No. SBC2013-14792.

[21] Fregly, C. D., Kim, B. T., De Witt, J. K., and Fregly, B. J., 2014, "Model-Based Recommendations for Reducing Back Loads During Squat Exercise on the International Space Station," 7th World Congress of Biomechanics, Boston, MA, July 6–11.

---

[3] https://simtk.org/home/aredsimulation