Musculoskeletal Human-Spacesuit Interaction Model

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Abstract—**Extravehicular Activity (EVA) is a highly demanding activity during space missions. The current NASA spacesuit, the Extravehicular Mobility Unit (EMU), might be thought of as the 'world's smallest spacecraft' and is quite an engineering achievement. However, the EMU has also led to discomfort and musculoskeletal injuries, mainly due to the lack of mobility in the pressurized suit that makes moving and operating within the suit challenging. A new musculoskeletal modeling framework is developed in OpenSim to analyze human-spacesuit interaction and musculoskeletal performance during EVA. Two spacesuits are considered: the current EMU and NASA's Mark III spacesuit technology demonstrator. In the model, the effect of the spacesuits is represented as external torques applied to the human body, based on experimental data. Muscle forces during knee flexion/extension are calculated and compared in "suited" and "unsuited" conditions. Results suggest that the maximum peak force exerted during knee flexion significantly increases from unsuited conditions to Mark III-suited conditions to EMU-suited conditions. In particular, the peak forces exerted by the biceps femoris long head (BFL), the gastrocnemius (GM), the gracilis (GR), and the sartorius (SR) knee-flexor muscles are significantly higher in "suited" conditions. Conversely, the knee-extensor muscles do not show significant differences between the unsuited and suited conditions. The musculoskeletal analysis provides new insights into human-spacesuit interaction and musculoskeletal performance in "suited" conditions, and contributes to the assessment of astronaut health and safety during EVA, informing flight surgeons, EVA operation teams, researchers and spacesuit designers.**

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1. INTRODUCTION

Extravehicular Activity (EVA) is one of the most challenging activities that astronauts need to accomplish in space, and maintaining health and comfort inside the spacesuit is critical. The Extravehicular Mobility Unit (or EMU) is the current United States (US) spacesuit, and is pressurized to 29.6 KPa (4.3 psi). This high pressure environment has led to minor (and some major) musculoskeletal injuries and discomfort
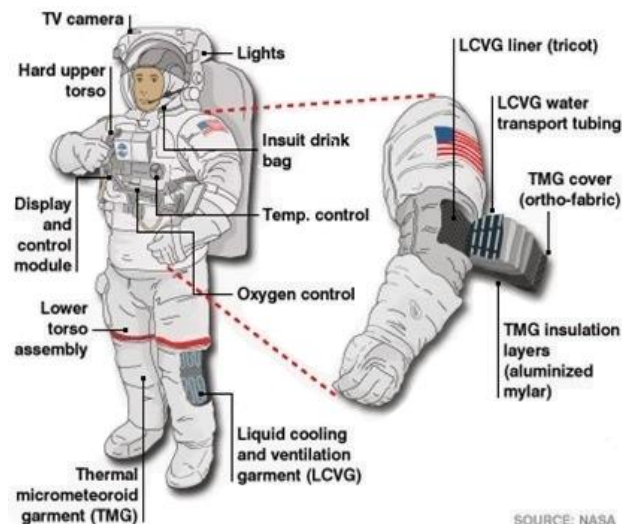
episodes that could affect astronauts' performance in a space mission [1, 2].

The EMU is pressurized to 29.6 KPa, using 100% oxygen for spaceflight and a mixture of nitrogen and oxygen (nitrox) for training. It is made with 14 different layers, and it consists of three main components [3], as shown in Figure 1:

- **The Liquid Cooling and Ventilation Garment (LCVG).** This piece of garment made of nylon and spandex covers the whole body and its main objective is to eliminate the excess body heat by water circulation through the garment.

- **The Spacesuit Assembly (SSA).** This includes a fiber hard shell that covers the torso called the Hard Upper Torso (HUT), the arm and glove assembly, and the lower torso assembly (waist, lower torso, legs and feet).

- **The Life Support System (LSS).** It refers to the backpack that contains oxygen, water, and the necessary electrical components amongst others.

Figure 1 – Different components of the EMU

Injuries during Extravehicular Activity

Injuries more often occur during training, but they can also occur during spaceflight.

Injuries during training—Extravehicular activity training is mainly conducted at the Neutral Buoyancy Laboratory (NBL), located at NASA Johnson Space Center, in Houston,

Texas. The NBL facility consists in a 23.8 million liter water tank where astronauts can simulate EVA in weightlessness. It contains full mock-ups of the International Space Station (ISS) and other space structures. Astronauts spend many hours training in the NBL and they can suffer injuries not seen in orbit due to the presence of gravity. Astronauts train approximately 11 hours in the NBL for each EVA hour planned in a space mission. In addition, the amount of training has increased over the past 10 years because of the increasing demands related to the ISS integration and operations. Thus, minor (and some major) injury incidences and discomfort episodes have become more frequent among the astronaut corps [1–4].

Injuries during spaceflight—Astronauts can also suffer EVA injuries during spaceflight. Mobility inside the spacesuit is very limited and difficult due to the rigidity and stiffness of the gas-pressurized spacesuit in the vacuum of space. In addition, astronauts often need to work at the boundary of their work envelope, exerting a huge amount of force against the suit [1–4].

2. EVA INJURY ANALYSIS

EVA injuries can be divided in two different groups: contact injuries and strain injuries.

Contact Injuries

Contact injuries refer to contusions, abrasions, or hard impacts with the spacesuit. For example, when astronauts are training in the pool in inverted positions, the presence of gravity makes them shift inside the spacesuit (see Figure 2), creating hard contact forces on the shoulders [3, 4]. Shoulder injuries during training are one of the most common injuries during the past few years [5]. They may be associated with the use of the new version of HUT called "planar". The planar HUT was introduced in the early 90s due to safety issues with the old pivoted version [6, 7]. The pivoted HUT allowed greater shoulder mobility, but it is only used for training if astronauts have a previous shoulder injury or if they need better mobility for medical reasons. Other contusions often occur on the extremities: arms (specifically elbows and wrists), and legs (particularly knees and ankles). The hip and trunk often impact with the HUT and bearings, and poor fitting boots cause loss of feeling, hard impacts, and abrasions [5, 7].

Several countermeasures are currently being used to mitigate to some extent astronaut injuries during EVA. Astronauts use comfort pads to minimize contact injuries with the spacesuit. There are different padding types available, and astronauts and the suit technicians decide which ones and how many they want to use. Pads might be located in all these body areas: lateral, back, chest, crotch, knee, and shoulder. Other countermeasures include the use of a harness to avoid shoulder contact with the spacesuit, boot size inserts, comfort gloves and socks, and the use of topical applications [1, 5, 7].
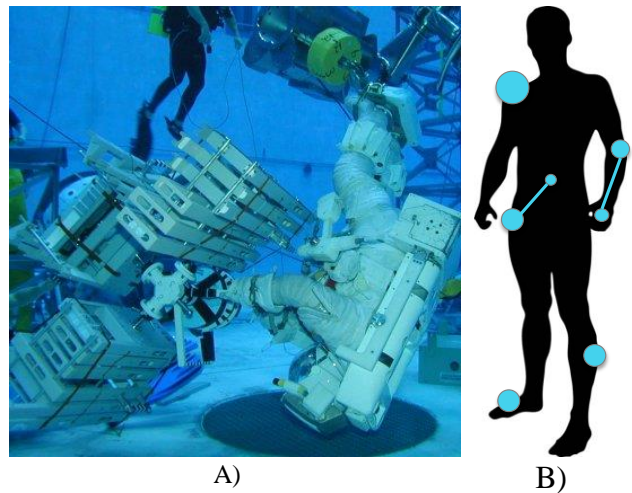
Figure 2 - A) Astronaut in an inverted position during NBL training (*NASA*). B) Most common injury locations during EVA [4]
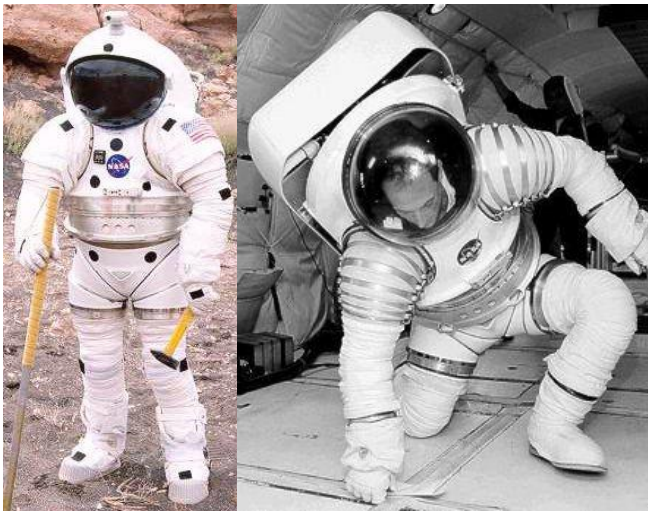
Strain Injuries

Strain injuries are due to overuse, repeated movements, and development of high muscle forces. For example, these injuries may occur when astronauts are manipulating heavy tools or working at the limit of their work envelope, forcing the shoulder joint against the spacesuit, amongst others [1].

Optimal suit fit plays an essential role in avoiding strain injuries. Therefore, suit technicians work very closely with astronauts before, during, and after each EVA training session at the NBL. Several databases keep track of the suit components, the amount and location of padding used, and also any incidence, if occurred, during their astronaut career.

Extravehicular Mobility Unit vs. Mark III

The EMU is currently used in the ISS. Thus, it is used in a microgravity environment, and it has not been designed to operate in different conditions such as the exploration of another planet. Its mobility is very limited, making inconceivable the use of the EMU in future Mars missions, where astronauts will need to explore long distances and construct their habitats.

The Mark III spacesuit technology demonstrator (MKIII) is a prototype developed by NASA in the late 80s for EVAs on the moon and Mars surfaces. This advanced rear-entry suit contains a mix of hard and soft components. Its modular architecture allows to accommodate multiple users. The MKIII initial operating pressure is around 55 KPa (8.3 psi) in order to reduce EVA pre-breathing time compared to the EMU. Then, the suit pressure gradually steps down to 29.6 KPa to conduct the majority of the EVA tasks. Despite its initial higher operating pressure, this suit concept provides a better mobility range, which is considered essential for planetary exploration [8]. As seen in Figure 3, the Mark III allows wearers to kneel and pick up objects from the ground.

Figure 3 – Mark III spacesuit (*Credit: NASA*)

A)   B)

Figure 4 – A) Concept representing human-spacesuit interaction (*Santos Inc/NASA*). B) "Gait 2354" computer model (*Opensim*)
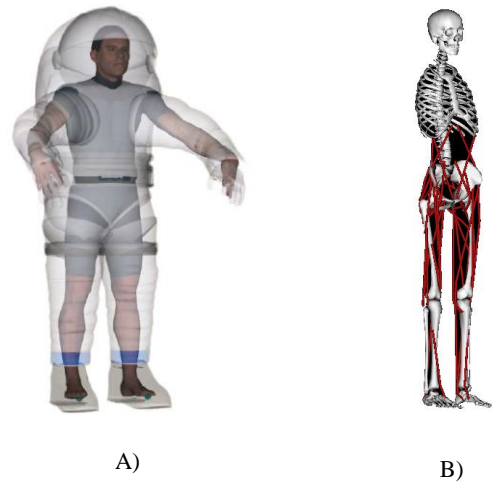
The purpose of this research effort is to gain a better understanding of the EVA injury mechanisms, particularly strain injuries caused by the EMU. The objective is to determine the extent to which muscle activity is affected by the presence of the highly-pressurized spacesuit. A musculoskeletal human-spacesuit interaction model is developed in order to quantify musculoskeletal performance of astronauts during Extravehicular Activity, and to assess their injury susceptibility. In particular, muscles forces generated during knee flexion/extension inside the EMU are analyzed and compared to "unsuited" and suited Mark III conditions.

3. METHODS

A new musculoskeletal modeling framework is developed to specifically analyze body-suit interaction and musculoskeletal performance during EVA. Figure 4A illustrates the concept of "looking inside the suit" to analyze how the human interacts with the suit. Necessary modeling capabilities include: human modeling, spacesuit modeling and a human-spacesuit interaction modeling capability to compute representative human performance measures.

Human modeling

The human-spacesuit interaction model is developed in OpenSim, an open-source musculoskeletal platform developed by Stanford University [9]. OpenSim offers numerous analysis capabilities [9, 10], including inverse kinematics (IK), inverse dynamics (ID), residual reduction algorithm (RRA) [11], and computed muscle control (CMC) [12, 13] among others. A big community of researchers has used OpenSim in the past, creating simulations of different human motions such as walking [14, 15], running [16], jumping [17], and squatting [18]. In addition, many musculoskeletal models are available to be used by the scientific community. Although it is open-source software, Opensim is one of the best references concerning biomechanics, and many scientific publications have attested the reliability of the program.

We implement a three-dimensional musculoskeletal model, which was first developed by Delp in 1990 [19]. The model has experienced many upgrades since then, but the essence and the main features are still the same. The representative astronaut model has height of 1.8 m. and mass of 75 kg. The model, shown in Figure 4B, does not include arms, but features a very accurate model of the lower body. It comprises 23 degrees-of-freedom and 54 muscles or musculotendon actuators, which are represented by the lines of action. The model includes 12 body segments: 1 "torso", 1 "pelvis", 2 "femur", 2 "tibia", 2 "talus", 2 "calcaneus", and 2 "toes". From its 23 degrees-of-freedom, 6 of them correspond to the coordinates of the model as a rigid body in the ground reference system (3 rotations + 3 translations); 3 of them correspond to lumbar coordinates (extension, bending, and rotation); and 2x7 correspond to lower coordinates (hip flexion, hip adduction, hip rotation, knee angle, ankle angle, subtalar angle, and metatarsophalangeal angle).

Spacesuit modeling

Given the lack of high fidelity spacesuit computational models, the main contribution of the spacesuits is modeled as external torques applied to the human body. Indeed, when astronauts bend their knee inside a pressurized suit, they work against the extra resistance added by the spacesuit to their motion. Thus, effects of the spacesuit joints can be replicated by applying external torques to the corresponding human model joints, based on experimental spacesuits torque-angle relationships.

EMU modeling—The EMU data were collected in the Man–Vehicle Laboratory at the Massachusetts Institute of Technology (MIT). The torque-angle relationships from different joints were measured using an instrumented robot inside a spacesuit [20]. Figure 5 shows the Space Suit Robot Tester used to take the EMU measurements. This technique has several advantages. First, it provides precise joint torque measurements without interfering with the subject's motion or using invasive instrumentation. In addition, previous

experimental results suggest that empty-suit (i.e., without a subject inside the spacesuit) measurement techniques may underestimate the real torques needed to bend the spacesuit's joints [21]. Empty-suit measurements do not account for contact between the wearer and the suit. Moreover, the larger volume inside the suit during empty-suit testing possibly contributes to the underestimation.

The EMU knee flexion/extension torque as a function of the knee angle (α) is shown in Figure 6. The initial position corresponds to $\alpha = 0$ degrees, located at the bottom left of the figure. In this position, the leg is entirely extended such that the thigh and the shank are completely aligned. The upper red line represents the spacesuit torques corresponding to different knee angles from 0–100 degrees during knee flexion motion. At the point of maximum knee flexion, corresponding to $\alpha = 100$ degrees, the torque induced by the EMU is 25 Nm. On the other hand, the bottom blue line represents the EMU torques corresponding to knee angles from 100 to 0 degrees during knee extension motion. The graphic shows a hysteretic behavior that is characteristic of highly pressurized spacesuits. The hysteresis is due to the loss of energy incurred in the mechanical deformation of the suit [21]. These external torques are applied to the musculoskeletal model to represent the effects of the spacesuit. Thus, the magnitude of the torque applied depends not only on the knee angle at each instant, but also on the direction of the motion: flexion or extension.

Mark III spacesuit modeling—The MKIII data were collected at the Johnson Space Center using the "modified fish-scale method" [22]. This method entails a measurement of the external force necessary to bend the spacesuit joints through their full range of motion. This force is then multiplied by the distance to the estimated position of a human joint center to obtain torque values. The angle of the joint was also measured using a gyro enhanced orientation sensor. In this method, the spacesuit is empty and pressurized to 29.6 KPa.
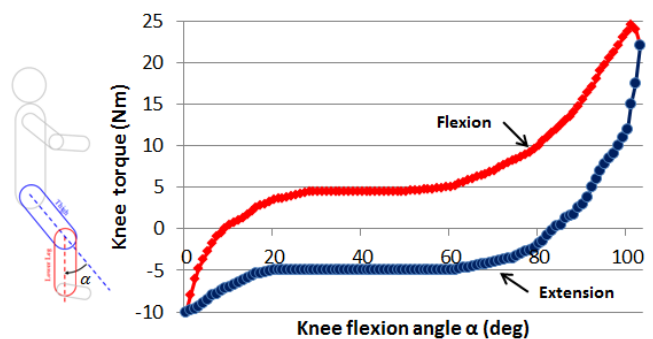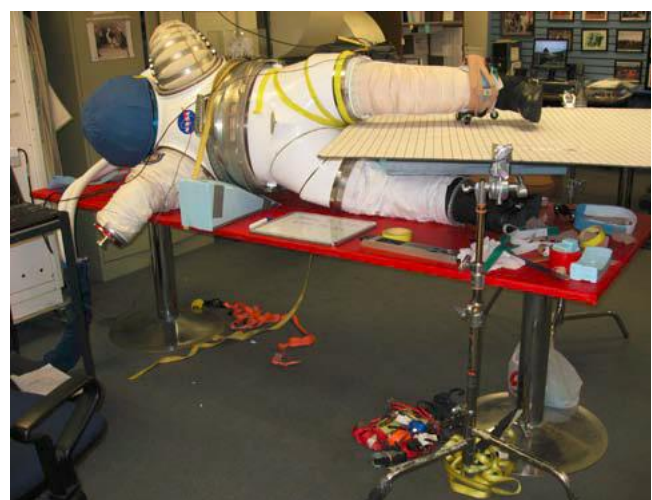

Figure 6 – EMU knee flexion/extension angle-torque relationship (adapted from [20])

The configuration setup during the knee flexion/extension measurements is shown in Figure 7. During the test, the knee motion was in a plane parallel to the ground to avoid gravity effects as much as possible. The rest of the suit was strapped to the table to restrain its movement and thus, attain a good isolation of the knee motion. The suit was tested without the Thermal Micrometeoroid Garment (TMG) or outer layer installed.
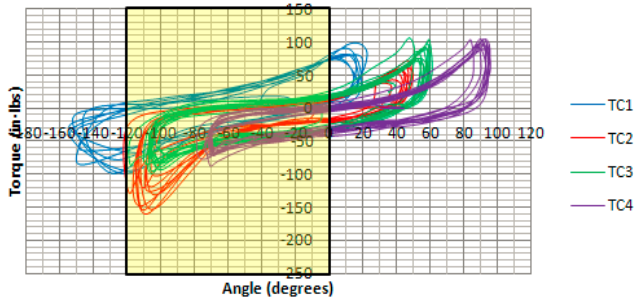
The MKIII knee flexion/extension torque was measured four times by different test conductors (TC), in the context of the validation of the modified fish-scale methodology. Figure 8 shows the four torque measurements through a wide range of angles. The values corresponding to the test conductor number three (TC3) were considered the ones more representative, since this particular trial includes improvements based on trials 1 and 2 in order to have more repeatable measurements [22]. The yellow shadow indicates the reference range of motion (ROM) requirements. A more detailed explanation of the methodology used to generate the data shown in Figure 8 can be found in [22].
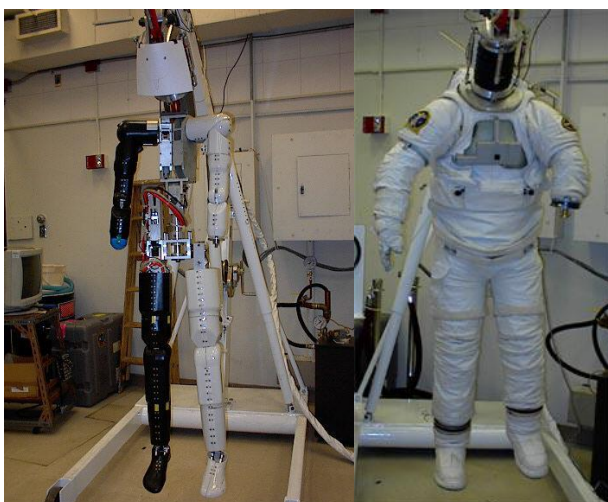
Figure 5: Robotic Space Suit Tester [20]

Figure 7 - Mark III test setup [22]

Figure 8 – Mark III knee flexion/ extension angle – torque relationships measured by 4 operators [22]

Figure 9 – Mark III knee flexion/extension angle-torque relationship (adapted from [22])

The MKIII knee flexion/extension torque as a function of the knee angle (α) applied to the musculoskeletal model is primarily based on the TC3 angle-torque relationships, and it is shown in Figure 9. This graph has been constructed in a conservative fashion, taking into account the highest TC3 torque values within the reference ROM, as well as some margin beyond those values. In addition, the angle reference system used in Figure 8 has been renamed to match the same notation used in the EMU simulation. Lastly, imperial units have been converted to international units (1 in lb = 0.112984829 Nm.)
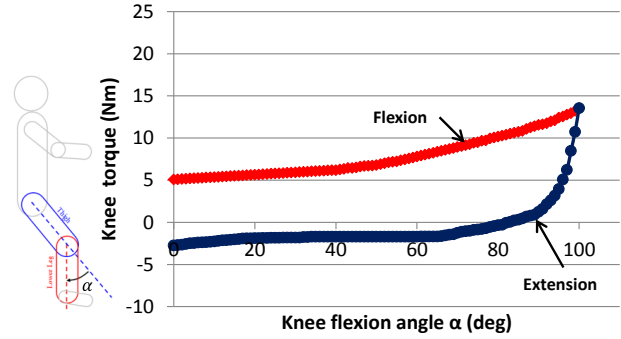
The knee flexion/extension angle-torque relationships corresponding to the EMU and MKIII present similar overall shapes. In both cases, torque values during knee flexion are higher than knee extension, and the highest torque value is encountered at the maximum knee flexion angle. However, the range of knee angles tested on the MKIII (from α = -60º to 110º) is wider than the EMU range (from α = 0º to 100º). This difference in the testing methodology explains the discontinuity observed between the MKIII flexion and extension curves at the lower end in Figure 9, a chart that only represents the more realistic ROM from α = 0º to 100º.

Human-Spacesuit interaction modeling

Motion data and ground reaction forces from two subjects (two replications per subject) were collected at the Computer Science and Artificial Intelligence laboratory located at MIT. A VICON® (Los Angeles, USA) motion capture system tracked the movement of thirty-five reflective markers placed at specific locations on the subjects' body, while performing left knee flexion/extension movements. Figure 10 shows the position of the leg markers during the motion capture data collection. The two subjects were of similar age and they had similar physical complexion. Their age, weight, and height are shown in Table 1.

Table 1 – Subject data

Subject	Age	Weight	Height
1	24 years	80.00 Kg	1.83 cm
2	26 years	72.12 Kg	1.80 cm

These data were processed and integrated in OpenSim, and several steps were performed to compute accurate muscle forces, namely: scaling (SC), inverse kinematics (IK), residual reduction algorithm (RRA) implementation, and computed muscle control (CMC). In the scaling process, the generic musculoskeletal model is scaled to match the anthropometry of the subject. The dimensions of the body are adjusted as well as the mass properties (mass and inertia tensor) of the different body segments. The inverse kinematic tool determines the joint angles and position of the model that best match the experimental kinematics or marker trajectories. The IK solver minimizes the sum of the weighted square marker errors, term shown in Equation 1.

$$\min_{q} \left[\sum_{i \in markers} w_i \left\| x_i^{exp} - x_i(q) \right\|^2 \right] \qquad (1)$$

Subject to musculokeletal model

q: vector of generalized coordinates being solved
w_i: weight of marker i
x_i^{exp}: experimental position of marker i
$x_i(q)$: position of marker i on the model

Weighted least squares problem

The main objective of the RRA algorithm is to improve the dynamic consistency of the simulation by slightly adjusting joint angles. These inconsistences may come from modeling assumptions (i.e. the model does not have arms), noise, or measurement errors. As a result, the recorded ground reaction forces and the estimated marker accelerations (based on maker tracking) do not comply with Newton's Second Law. Hence, residual forces and moments are applied to maintain the balance of the model. These are non-physical forces and moments that are applied to the reference segment of the model (i.e. pelvis) in order to improve the dynamic consistency of the simulation. In a further step, these residual values are minimized by slightly changing the kinematics (joint angles root mean square, or RMS < 2 deg.) This approach reduces the size of the residuals without eliminating them entirely, which has been proven to be a better approach to compensate for modeling assumptions and unmodeled dynamics [11].
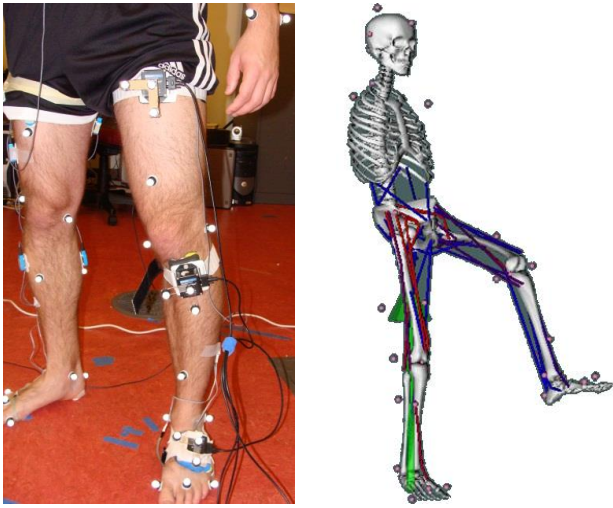
Figure 10 – Motion capture data collection and modeling in OpenSim

The CMC tool computes a set of muscle activations and forces that drives the dynamic model to track the desired kinematics [12]. It uses a proportional derivative control in a closed loop to track the desired trajectories. At each step, the equation of motion is resolved to calculate the torque value at the different joints. At that point, in order to solve for muscle redundancy at each joint, an optimization algorithm is solved to allocate forces amongst the different muscles. The CMC makes use of the musculotendon actuator model and the force-length- velocity relationships [23–25] captured in the musculoskeletal model.

Finally, in order to simulate "suited" conditions, EMU and MKIII knee torque data based on experimental torque-angle relationships have been incorporated into the simulations as external torques. Figure 11 shows the different steps of the methodology, specifying the inputs and output of each phase.
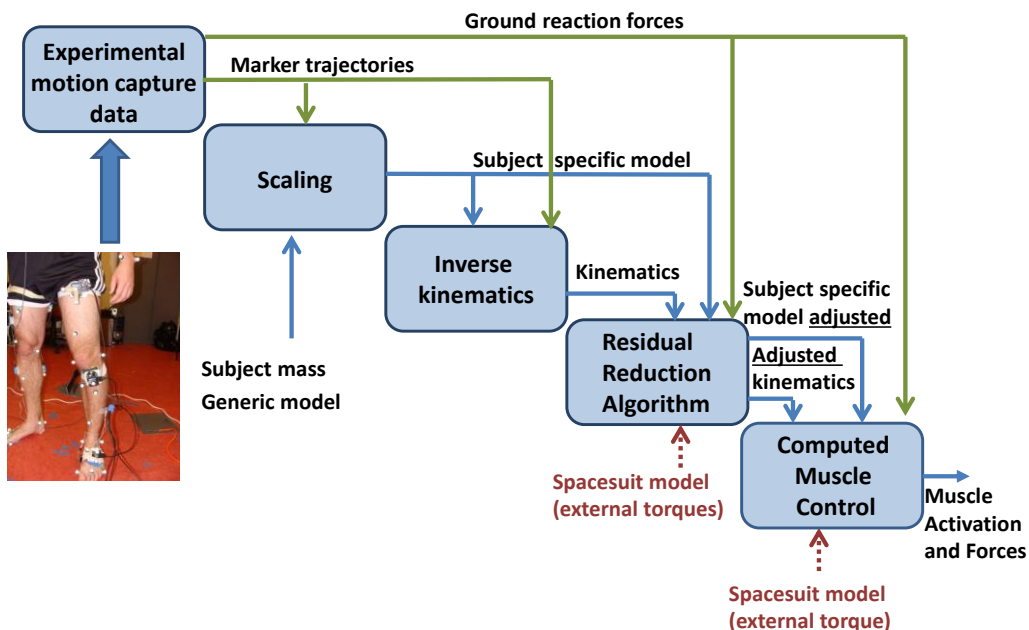
Experimental design and analysis

Subjects performed knee flexion/extension movements from knee angle α = 40º to 100º, and the entire movement lasted about 1 second. From all the movement recordings, the two most accurate trials (according to the knee angle criteria) were selected per subject. The knee angle from one of the subjects during the simulation is shown in Figure 12.

The musculoskeletal model includes the principal muscles to perform knee flexion/extension movements. The knee flexor muscles include the biceps femoris long head (BFL), the biceps femoris short head (BFS), the gracilis (GR), the sartorius (SR), and the gastrocnemius (GM). The knee extensor muscles include the rectus femoris (RF), and vastus intermedialis (VI). Muscles forces exerted by knee flexors and knee extensors were calculated for all three conditions: unsuited, EMU-suited, and MKIII-suited.

Statistical tests were performed using SPSS Statistics 22 software (IBM Corporation). Peak forces were tested for homoscedasticity using the Levene's test, and for normality using the Kolmogorov-Smirnov test. Some of the data samples didn't satisfy the normality requirement (BFS, SR, VL and Total Extension), most likely due to the small sample size. When normality was satisfied, a mixed ANOVA was used to compare peak forces, using the subjects as the random blocking variable in order to account for inter-subject differences. In addition, pairwise comparisons were calculated using the Tukey *post-hoc* procedure. Otherwise, a non-parametric Kruskal-Wallis (KW) test was used combined with pairwise multiple comparisons with adjusted p-values for *post-hoc* testing. In all cases, significance was taken at the $\alpha = 0.05$ level. Force values are presented as the average ± standard deviation.
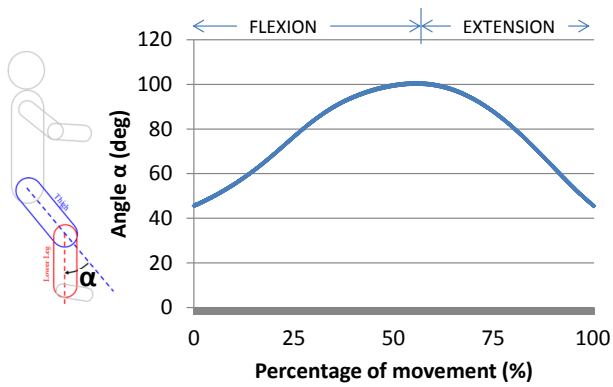

Figure 11 – Modeling methodology showing the different steps to analyze muscle dynamics

Figure 12 – Knee angle during the simulation

4. RESULTS AND DISCUSSION

Total Forces

Knee flexion and extension total forces for one subject during one of the trials are shown in Figure 13 and Figure 15 respectively. These figures represent the sum of the forces exerted by all the knee flexor muscles (BFL, BFS, GR, SR, and GM in Figure 13), and all the knee extensor muscles (RF and VL in Figure 15) involved in the movement.

Results suggest that the total force exerted by all knee flexors is generally higher across the movement in suited conditions, particularly in the EMU (Figure 13). The three conditions present a similar force profile, although both suited conditions require higher force earlier in the movement in order to account for the presence of the spacesuits. Total knee extensor forces do not show notable differences across conditions (Figure 15).

Maximum peak forces including all four trials (2 subjects, 2 replications per subject) in each condition are summarized in Table 2. Pairwise comparisons on flexor peak forces show significant differences between the three conditions: "unsuited" and "EMU-suited" conditions ($p<0.001$); "unsuited" and "MKIII-suited" conditions ($p<0.001$); and "EMU-suited" and "MKIII-suited" conditions ($p=0.005$). A box plot with the pairwise comparisons is shown in Figure 14. These results are consistent with the fact that the MKIII spacesuit presents a better mobility, and therefore represents an improvement with respect to the EMU. On the other hand, extensor peak forces do not present significant differences between the three conditions, as shown in the box plot in Figure 16.
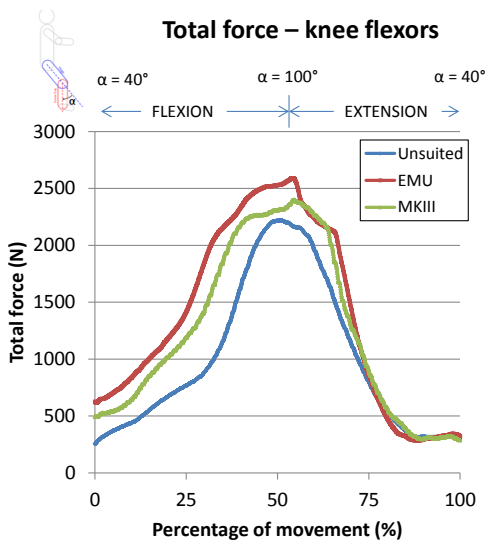

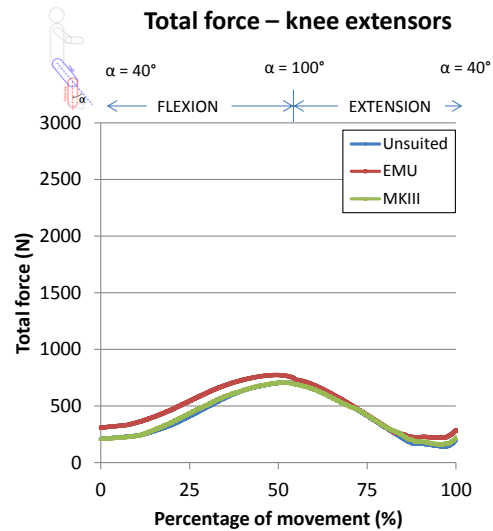**Figure 13 – Total knee flexors force (subject 1)**
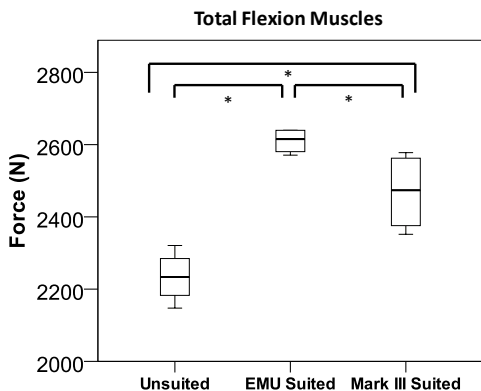

Figure 15 – Total knee extensors force (subject 1)

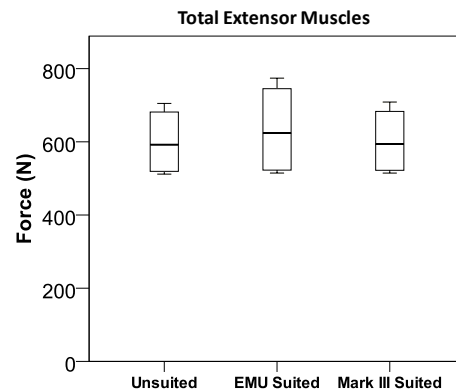**Figure 14 – Pairwise comparisons (all trials; *p < 0.05)**

Figure 16 - Pairwise comparisons (all trials; *p < 0.05)

Table 2 – Peak forces in Newton (N)

Muscles	Non Suited	EMU Suited	MKIII Suited	P value
Total Flexors	2234±72	2610±35	2469±110	**<0.001**
Total Extensors£	600±96	634±131	603±95	0.584

£ use of non-parametric test KW

Individual Muscles Forces

Individual muscles forces were calculated using the CMC tool described in previous sections. Muscles forces exerted by knee flexors and knee extensors are shown in Figure 17 and Figure 18 respectively, for all three conditions: unsuited (top), EMU-suited (middle), and MKIII-suited (bottom). These figures represent the individual flexor (Figure 17) and extensor (Figure 18) muscles forces exerted during the movement of one subject during one of the trials. Table 3 and Table 4 summarize peak values corresponding to individual flexor and extensors muscle forces respectively. Finally, Figure 19 shows the pairwise comparisons for the four flexor muscles that present significantly different peak forces (BLF, GR, GM, and SR).

Flexor muscles—Results concerning the knee flexor muscles (Figure 17) suggest that the two muscles most involved in the movement are BFL and the BFS, and the rest of the flexor muscles do not seem to contribute too much to the movement. The BFL and BFS are big muscles that can generate a higher force and therefore, they are more solicited during the movement. The BFL and BFS have similar profiles across all three conditions, although the BFL in both EMU and MKIII suited conditions develops a higher peak force and presents a wider shape, indicating that the presence of the spacesuits solicits longer and more intense activation of this particular muscle. Pairwise comparisons on BFL peak forces show significant differences between "unsuited" and "EMU-suited" conditions (p=0.002), and "unsuited" and "MKIII-suited" conditions (p=0.004). A box plot with the pairwise comparisons is shown in Figure 19.

The flexor muscle that seems more affected by the presence of a spacesuit is the GM. In EMU-suited conditions, this muscle shows a clear increase in its activation patterns. In the MKIII conditions, the GM also presents an increase in force developed, although this increase is not as large as in the EMU-suited conditions. These results are consistent with the lower knee torque imposed by the MKIII. All in all, the GM seems to be the principal muscle handling the effects of the spacesuit. Pairwise comparisons on GM peak forces show significant differences between all three conditions: "unsuited" and EMU-suited conditions (p<0.001); "unsuited" and "MKIII-suited" conditions (p=0.024); and "EMU-suited" and "MKIII-suited" conditions (p=0.001). A box plot with the pairwise comparisons is shown in Figure 19.

In addition to the BFL and GM muscles, the *gracilis* muscle (GR) also shows significant differences between the "unsuited" and "suited" conditions. Pairwise comparisons on BFL peak forces show significant differences between "unsuited" and "EMU-suited" conditions (p=0.009), and "unsuited" and "MKIII-suited" conditions (p=0.024). Finally, the *sartorius* muscle (SR) also shows slightly significant differences between the "unsuited" and "suited" conditions using a non-parametric statistical procedure. Pairwise comparisons on SR peak forces show significant differences between "unsuited" and "EMU-suited" conditions (p=0.048). Box plot are shown in Figure 19.

Extensors muscles—Similarly to the behavior of extensor total forces, individual knee extensor muscles do not show major differences in their profiles between "unsuited", "EMU-suited", or "MKIII-suited" conditions (Figure 18). Table 4 shows the peak values for the extensor muscles including all trials, and the statistical analysis did not reveal any significant difference between any of them. These results are consistent with the intrinsic nature of highly pressurized spacesuits, which have a tendency to come back to its neutral position. Thus, extensor muscles do not seem to be particularly challenged during "suited" activities involving this form of knee flexion/extension movements.

Table 3 – Knee flexors peak forces in Newton (N)

Flexors Muscles	Non Suited	EMU Suited	MKIII Suited	P value
Biceps femoris long head (BFL)	1316±57	1448±33	1428±40	**0.001**
Biceps femoris short head (BFS)£	673±20	669±24	674±19	0.668
Gracilis (GR)	135±6	147±2	145±4	**0.008**
Gastrocnemius medialis (GM)	105±25	296±33	175±24	**<0.001**
Sartorius (SR)£	134±23	153±2	153±3	**0.046**

£ use of non-parametric test KW

Table 4 - Knee extensors peak forces in Newton (N)

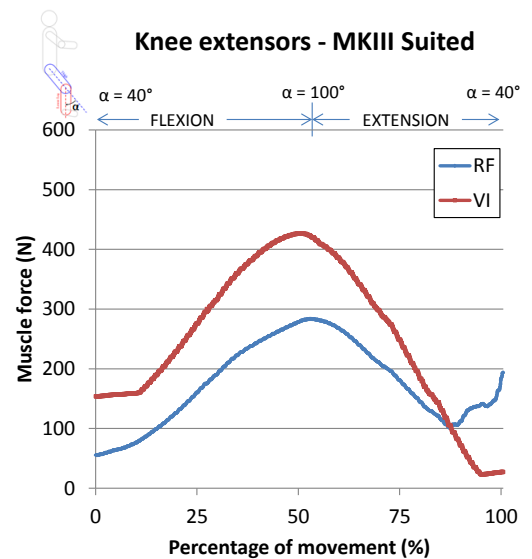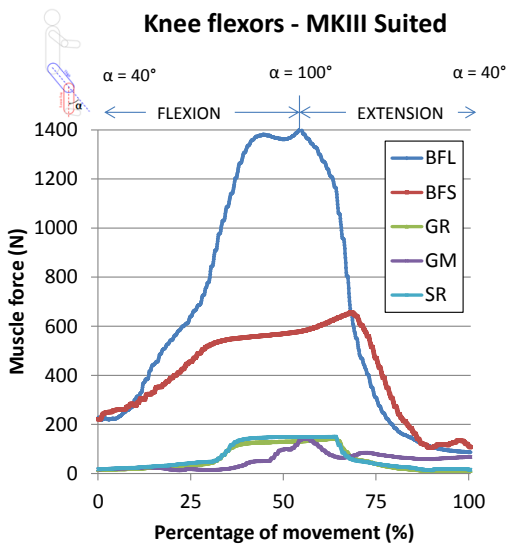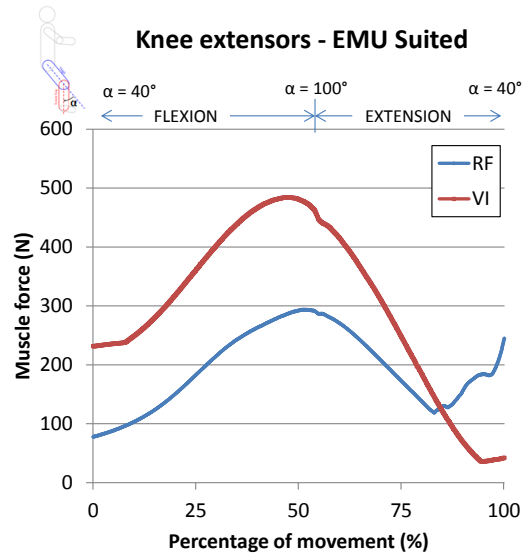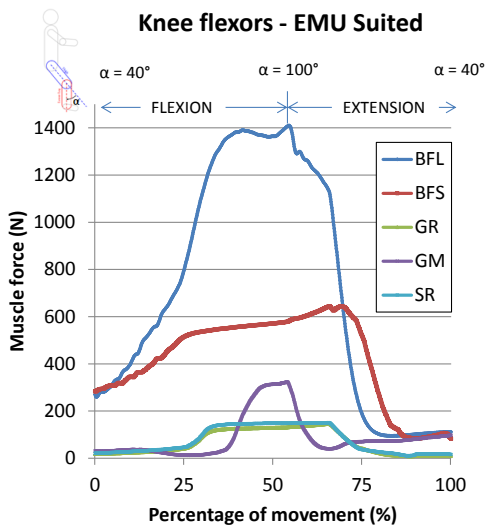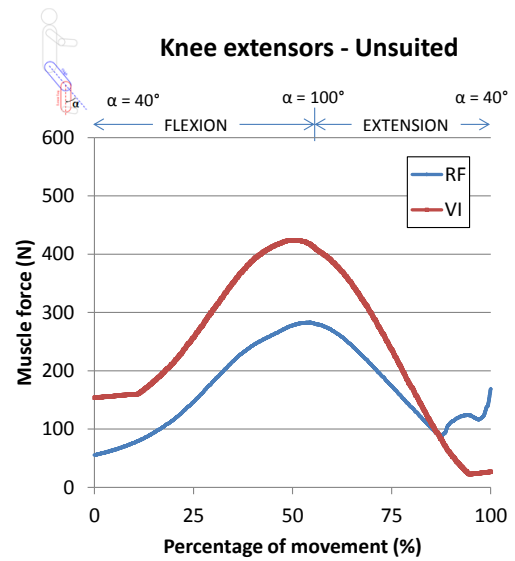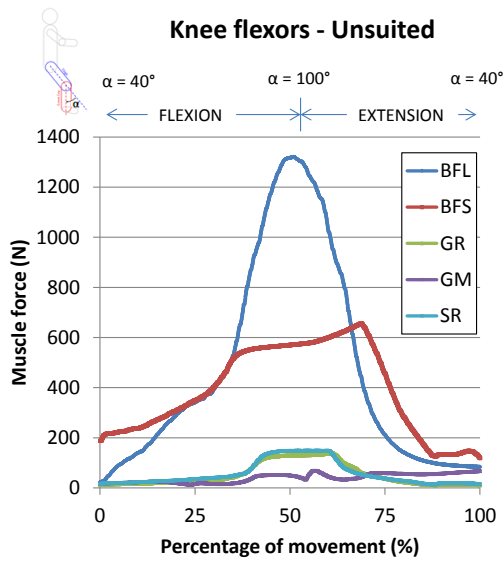| Extensors Muscles	Non Suited	EMU Suited	MKIII Suited	ANOVA P value
Rectus femoris (RF)	274±8	280±10	276±7	0.645
Vastus intermedialis (VI)£	332±88	360±119	333±88	0.584

£ use of non-parametric test KW

Figure 17 – Knee flexors muscle forces (top to bottom) exerted while unsuited, EMU suited, and MKIII suited

Figure 18 - Knee extensors muscle forces (top to bottom) exerted while unsuited, EMU suited, and MKIII suited

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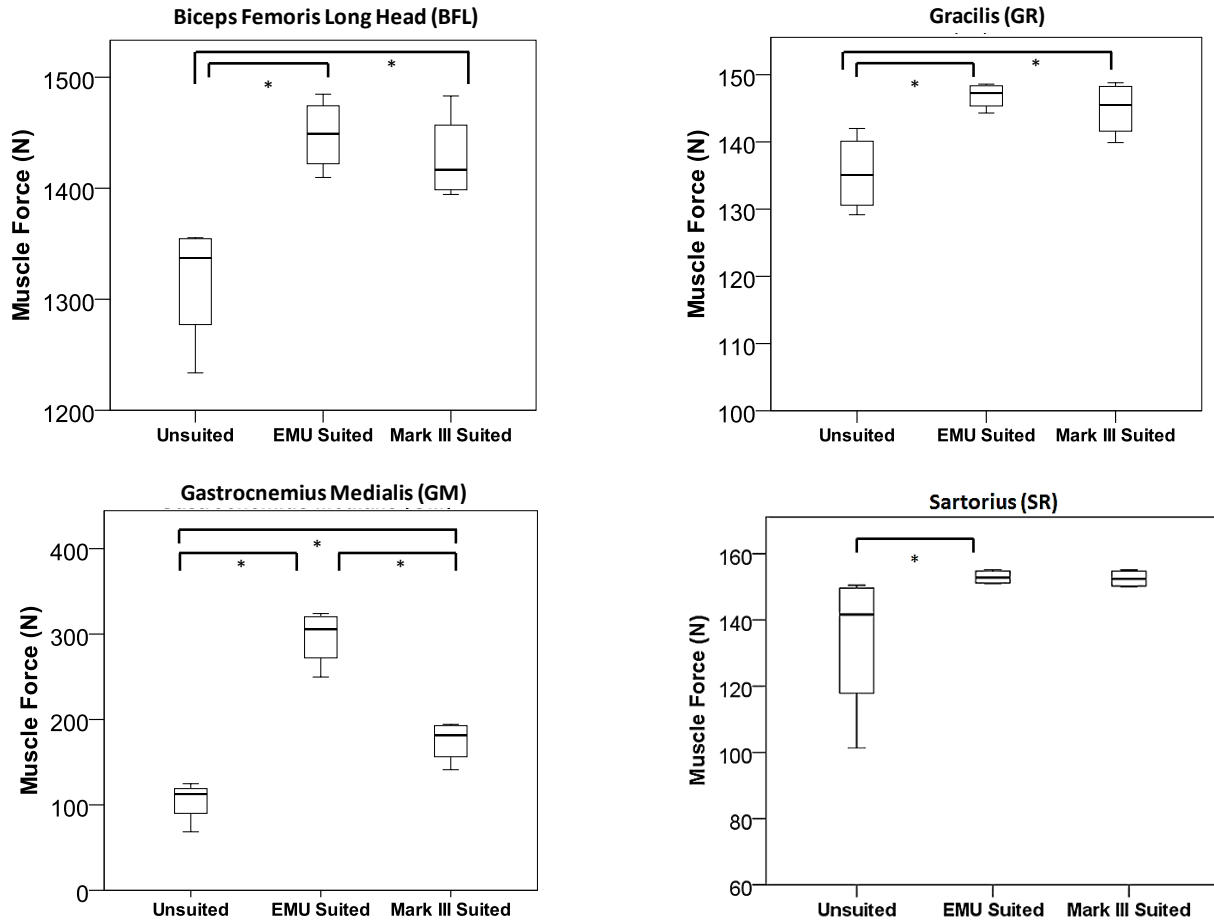
Figure 19 – Pairwise comparisons of some flexor muscles (all trials included; *p < 0.05)

Discussion

The musculoskeletal framework developed gives new insights in to the musculoskeletal behavior inside the spacesuit and the human-spacesuit interaction during EVA. This research effort focuses on the knee joint, and is recommended for future expansion to other joints, and eventually to other spacesuits if the joint-angle relationships are known.

The analysis captures the motion constraints imposed by highly pressurized spacesuits during flexion motions, or motions involving moving away from the neutral position. This is particularly true in the EMU, a spacesuit that is not designed for surface operations (e.g., walking) and therefore does not facilitate knee motions. In addition, the musculoskeletal analysis also captures the higher mobility nature of the Mark III spacesuit, which is a spacesuit designed for planetary exploration. On the other hand, results suggest that knee extension motions do not seem to be affected by the presence of the spacesuits. Hence, the extensor muscles are not particularly challenged during the representative EVA activities. This is consistent with the natural behavior of

pressurized spacesuits, which have a natural tendency to come back to the neutral position.

In terms of validation, muscle forces results are supported not only by the established reputation of Opensim, but also by the consistency of results with respect to the inputs, allowing a good comparison between the different suit conditions. Further validation would require the use of electromyography (EMG), although the feasibility of this technique inside a pressurized spacesuit hasn't be assessed yet, not to mention the safety issues associated with the introduction of new electronic components in a spacesuit.

One important aspect to take into account when analyzing and comparing the results between the two spacesuits is the different methodologies used to gather the joint-torque relationships from the EMU and Mark III. As previously stated, the Mark III torque values were taken in empty-suit conditions and they could be underestimating the real torque values. In addition, the "modified fish-scale method" used to measure the Mark III joint torques is highly variable including measurement errors such as inconsistent cycling of the joint, indirect forces into a load cell when pushing and pulling, differences in the initial angle position or in the rate of joint

cycling, and accelerometer drift due to an insecure cell attachment [22]. These variables were identified and mitigated to the best extent in a final round of testing, which correspond to the simulation presented in this paper. In the absence of more accurate joint torque measurements, this research effort is the most current musculoskeletal analysis for the Mark III and the EMU spacesuits during EVA operations.

Ultimately, the output from this musculoskeletal framework and analysis can be related to muscle injury susceptibility. One of the potential mechanisms that may cause muscle injuries is the muscle peak force developed during a particular movement or activity [26, 27]. Previous literature suggests that when peak forces exerted by a particular muscle remain below 125% of the maximum isometric force (maximum force that a muscle is able to generate in isometric conditions), there is minimal risk of injury. However, there is a high chance of injury if the peak force equals or exceeds 150% of the maximum isometric force of the muscle [26]. For reference, Table 5 shows the maximum isometric forces of muscles included in the musculoskeletal human model used in this research work. Although a more in-depth analysis is needed, thresholds based on maximum isometric force values can be used as preliminary references to assess potential muscle damage.

Besides peak forces, other injury mechanisms include eccentric contractions, tissue elongation or strain, elevated strain rates, and activation time and rates [26, 27]. The musculoskeletal analysis being developed has the capability to provide to some extent this information. Fatigue and previous injuries are also important factors to consider. A future injury susceptibility tool could take into account all these factors and weight them appropriately in order to assess muscle injury during EVA activities.

5. CONCLUSION

The musculoskeletal framework developed herein informs different sectors of the human spaceflight community, including flight surgeons, EVA operation teams, researchers, and spacesuit designers. The musculoskeletal analysis contributes to the assessment of the human performance and astronaut health inside the spacesuit, as well as astronaut safety during EVA operations.

Table 5 – Maximum isometric forces in Newton (N)

Muscles	Max. Isometric Force (N)
Biceps femoris long head (BFL)	2700
Biceps femoris short head (BFS)	804
Gracilis (GR)	162
Gastrocnemius medialis (GM)	2500
Sartorius (SR)	156
Rectus femoris (RF)	1169
Vastus intermedialis (VI)	5000

The feasibility of individual EVA tasks can also be studied, by assessing if the astronaut musculoskeletal system stays within a safe envelope. Furthermore, future spacesuit design can benefit from the musculoskeletal framework being developed, for example imposing torque limits to the next generation of spacesuit.

Ongoing research includes analysis of motion capture data from several subjects wearing the EMU and Mark III spacesuits. Future work includes refining the spacesuit model by incorporating spacesuits torques in other joints, and using a more accurate human musculoskeletal model that contains musculo-tendon actuators in the upper torso and arms.

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BIOGRAPHIES

Ana Diaz *is a PhD candidate in the department of Aeronautics and Astronautics at MIT. Her research interests focus on human spaceflight and space system engineering, with a strong emphasis on Aerospace Biomedical Engineering, Extra-vehicular Activity and Artificial Gravity. Prior to MIT, Ana worked for five years in Kourou (French Guiana) as a member of the Ariane 5 Launch team. In particular, she worked as a specialist in operations concerning the Ariane 5 upper stage (both cryogenic and storable) and ground systems. Ana has a background in aeronautical engineering from Universidad Politécnica de Madrid, Spain, and Supaero in Toulouse, France. She is a 2011 Fulbright fellow, and an active member of the Women's Graduate Association of Aeronautics and Astronautics at MIT.*

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