POLITECNICO DI MILANO

Master of Science in Biomedical Engineering

Department of Electronics, Information, and Bioengineering

Biomechanical Quantification of Muscle Loading to Improve the Quality of Microgravity Countermeasure Prescriptions for Resistive Exercise

Supervisor: Prof. Alessandra Laura Giulia Pedrocchi

Co-Supervisor: Prof. Manuela Galli

Co-Supervisor: Eng. Matteo Zago

The thesis of Master Degree

Author: Zeynep Melike Işılay

Academic year 2018-2019

Table of Content

Sommario

L'Advanced Resistive Exercise Device (ARED) è un'attrezzatura per l'allenamento della forza progettata dalla NASA che gli astronauti usano per mantenere la forza e la resistenza ossea e la resistenza nello spazio. Il dispositivo utilizza cilindri a vuoto a pistone con resistenza regolabile e un volano per il sistema che consente agli astronauti di caricare il carico e preservare la forza e la massa muscolare durante lunghi periodi nello spazio.

Lo scopo di questo studio è di valutare un livello di carico ottimale da utilizzare in ARED per ogni esercizio resistivo. È stata valutata la forza e il momento interni di ogni articolazione degli arti inferiori sviluppati durante quattro diversi esercizi resistivi e un livello di carico ottimale per mantenere la forza muscolare nello stato di microgravità.

La raccolta dei dati è stata condotta in normali condizioni di gravità con la partecipazione di un astronauta. I dati cinematici sono stati acquisiti dal sistema di motion capture ELITE-S2 e i dati di forza sono stati ottenuti dalle piastre di forza.

Per la fase di elaborazione dei dati, BTS SMART Analyzer è stato utilizzato per calcolare e valutare i parametri richiesti come traiettorie dei marker elaborati, dati GRF, accelerazione lineare e angolare, centro di massa, ecc. Alcune ipotesi consentivano di assemblare un set completo di parametri.

Le uscite consentono di organizzare un programma di esercizi ottimizzato e aumentare le conoscenze su come l'esercizio di resistenza in assenza di gravità influisce sul corpo. L'analisi dei dati e dei risultati ottenuti dimostra quanto sia importante l'acquisizione del movimento in condizioni di assenza di peso e la necessità di raccogliere dati accurati per valutare tutte le estremità. I risultati ottenuti sono soddisfacenti in termini di somiglianza e accuratezza rispetto agli studi pertinenti in letteratura e lo studio può essere ulteriormente basato sul miglior posizionamento del marcatore e sul posizionamento delle telecamere.

Abstract

The Advanced Resistive Exercise Device (ARED) is a strength training equipment designed by NASA that astronauts use to maintain preflight muscle and bone strength and endurance in space. The device uses an adjustable resistance piston-driven vacuum cylinders along with a flywheel to the system to provide loading for astronauts to experience load and preserve the muscle strength and mass during long periods in space.

The aim of this study is, to evaluate an optimal load level to be used in ARED for each resistive exercise. The internal force and moment of each joint in the lower extremity developed during four different resistive exercises and an optimal loading level to remain muscle strength in the microgravity state was evaluated.

The data collection was conducted under normal gravity conditions with the participation of one astronaut. Kinematic data were acquired from the ELITE-S2 motion capture system and force data were obtained from force plates.

For data processing stage, BTS SMART Analyzer was used to calculate and evaluate required parameters such as processed marker trajectories, GRF data, linear and angular acceleration, the center of mass, etc. Some assumptions allowed to assemble a complete set of parameters.

The outputs allow to arrange an optimized exercise program and increase the knowledge about how resistance exercise in weightlessness affects the body. The analysis of obtained data and results prove how important motion capturing in weightless condition and the necessity to gather accurate data to evaluate all extremities. The obtained results are satisfactory in terms of similarity and accuracy with respect to relevant studies in literature and the study can be further based on improved marker positioning and placement of cameras.

Acknowledgments

I would like to thank first Prof. Manuela Galli who allowed me to continue my project and accepted me in the Motion Analysis Laboratory at Politecnico di Milano. Additionally, I am really thankful to Eng. Matteo Zago because of his great patience, kind support, noble ideas, guidance and having been always available for my several questions and to have been such a great person. Moreover, I would like to thank my supervisor Prof. Alessandra Pedrocchi. They gave me the opportunity to learn a lot from this experience, both from a working discipline and personal point of view, providing me support and pieces of advice.

I learned much more than I could imagine from them during the thesis study. I am grateful to meet all Professors and be part of this project. Additionally, I would like to add my great thanks to my both Italian and Turkish friends, who are with me and made this master study great experience since from beginning and especially Panagiota who is the best friend that Politecnico di Milano gave me.

To all above, I am truly grateful for my family in Turkey who support me to have a new life in Italy. In every stressful condition, although we have a huge distance between us, they provided me better solutions and encouraged me about never give up.

List of Figures

1. INTRODUCTION

1.1. The ARED project

The International Space Station (ISS) is a research laboratory that has helped to increase human space exploration. Astronauts aboard the ISS do not feel the effects of gravity as we do on Earth. As the ISS orbits the Earth, both the vehicle and crew members are in a constant state of free-fall, causing astronauts to experience a feeling of weightlessness [1]. Since no sense of gravity would result in muscle deterioration and bone density loss so astronauts are prescribed exercise routines by exercise and rehabilitation specialists and medical doctors. Astronauts are scheduled to exercise approximately two hours per day to maintain their health while on the ISS.

Numerous types of exercise equipment have been used in reduced gravity to evaluate and maintain astronaut fitness. The Advanced Resistive Exercise Device (ARED) which is represented in figure 2.1 allows the crew to engage in resistive exercise onboard the ISS by simulating the use of free weights. This device is used to maintain muscle strength, bone strength, and endurance. The resistive force is generated by two piston/cylinder assemblies with an adjustable load. For bar exercises, the load can be adjusted from 0 to approximately 2,670 N (0 to 600 lbs on Earth or in a 1 g environment). For cable exercises, it can be loaded up to approximately 670 N (150 lbs in a 1 g environment). Astronauts can perform 29 different free-weight style exercises, including deadlifts, squats, heel raises, hip abduction and adduction, bench press, bicep curls, tricep extension, and upright rows. The ARED is attached to the structure of the ISS with a Vibration Isolation System (VIS) installed between ARED and the ISS to limit forces transmitted to the ISS when astronauts are exercising. Springs, dampers, and shock absorbers in the VIS keep ARED centered in its operational volume and minimize the forces transmitted to the ISS to maintain an environment conducive to science.

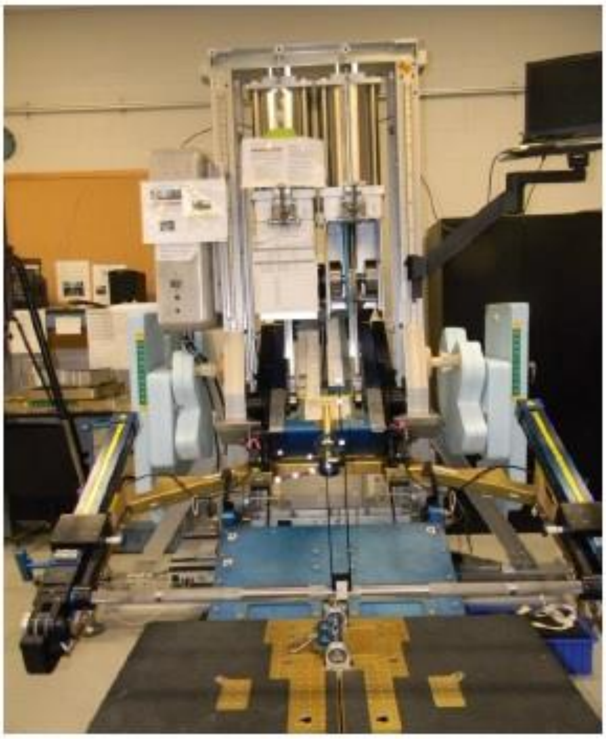


Figure 1. 1 The front view of ARED

To maintain muscle mass in microgravity is a critical issue. For any activity, reduced gravity leads to reduced mechanical loading on the 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. To maintain muscle mass special exercise device, for long-duration spaceflight was developed. The ARED provides several high resistance exercises. The Advanced Resistive Exercise Device (ARED) uses an adjustable resistance piston-driven vacuum cylinders along with a flywheel to the system to provide loading for crew members to experience load and maintain muscle strength and mass during long periods in space. The ARED has the capability to exercise all major muscle groups while focusing on the primary resistive exercise: squats, deadlifts, and heel raise.

The ARED allows performing a wide variety of high resistance exercises, including parallel squat exercise for maintaining leg muscle mass. During squat exercise, the astronauts hold the shoulder bar across the shoulders while standing on the ARED footplate. Two vacuum cylinders then apply a compressive load to the astronaut between shoulder bar and footplate. Vacuum cylinder loads are typically set to an Earth-level value plus 70% body weight to account for the lack of gravity. However, although ARED has been an effective exercise device for remaining body strength in specific loads, the effect of the case which is variations in load is unknown.

The most critical point is in which level ARED squat exercise is efficient in ISS with respect to earth-level and how much back and leg muscle moments are altered by simple adjustments on the footplate, is researched and answered by developing computational Model in OpenSim software platform. The load ranges and strength of the device were experienced in virtually modeled ARED. The three-dimensional multibody dynamic model of an astronaut on Ared system in OpenSim software and ARED machine computer-aided design (CAD) were constructed and combined. The musculoskeletal model is obtained by some modifications on already existing full body model in the OpenSim software library. Initially model has 37 degrees-of-freedom (DoF) includes the kinematic structure of upper and lower extremities. To assess the level of efficiency in the lower body, the upper body joints were omitted from the model and considered only 21 DoFs. In addition, by replacing 6 DoF ground-to-pelvis joint to ground-to-shoulders, calculation of inverse Dynamic loads on the shoulders instead of the pelvis is facilitated. After modification of skeletal model, the definition of the kinematic structure of the ARED and combination with a musculoskeletal model was figured out.

The ARED structure was modeled in the sagittal plane with 3 DoF planar joint which connects the ARED to ISS. All remaining ARED joints were modeled as pin joints. The link between the shoulder of the skeletal model and ARED shoulder bar was connected by a 3DoF planar joint to calculate reaction forces easily. The last step, which is a connection between feet of the skeletal model and ARED footplate was provided via weld constraints that allow for calculation of six reaction values (force and moment of force). In total ARED system has seven links closed kinematic chain possessing 4 DoFs in the sagittal plane.

The constructed astronaut-ARED system permit to mimic a hybrid approach which consists of forward and inverse dynamics on Earth and the ISS. In Complete ARED system, while the time-varying inputs were considered as sagittal plane joint motions of the body at which, back, hips, knees, and ankles, the varying outputs are predicted as a sagittal plane motion of ARED itself, the shoulder and foot reaction forces with altered CoP positions. The sagittal plane inputs are same both legs with an effective seven-link closed kinematic chain that ensures the symmetry in hips and ankles. In each squat movement, muscle moment outputs were assumed as a clue to reach that muscle force that is required for that movement.

To face leg muscle atrophy, astronauts on the International Space Station (ISS) often perform the squat exercise using the Advanced Resistive Exercise Device (ARED) [45]. 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.

The recent researches suggest that ARED functions maintain crew health in space. Crew members exercise daily on ARED to maintain their preflight muscle and bone strength and endurance [35].

Science Results for Everyone Exercising in space poses unique challenges, but without exercise, astronauts can lose up to 15 percent of their muscle mass, some of it permanently. The ARED investigation uses a piston and flywheel system to simulate free-weight exercises in normal gravity to work for all the major muscle groups through squats, deadlifts, and calf raise. ARED users see results similar to those from free-weight training, suggesting that it could be an effective countermeasure against loss of conditioning during space flight. While ARED's primary goal is to maintain muscle strength and mass, resistive exercise also helps astronauts increase endurance for physically demanding tasks such as spacewalks.

The ARED provides a load of up to 600 pounds for bar and 250 pounds for cable exercise and connects to a Space Station Computer (SSC) that makes it easier for crew members to follow a personalized exercise plan.

ARED consists of seven distinct assemblies:

1. Exercise Platform Subassembly mounts to the ARED structural frame and provides the surface from which to perform exercises. The platform houses two force plates, with 4 load cells installed under each plate to measure the reactive loads for all exercises.
2. Cylinder/Flywheel Assembly generates the loads for all exercises. The vacuum canisters provide the primary force while the flywheels provide the simulated

inertial component of the exercise as would be experienced on the ground. These are mechanical assemblies only.

3. Main Arm Assembly includes the wishbone arm and the lift bar components. Load cells were installed in the lift bar struts.
4. Arm Base Assembly includes the load adjustment mechanism, interfaces for the Cylinder/Flywheel Assembly, Main Arm Assembly, Cable Pulley Assembly, and the Frame/Platform Assembly. These assemblies contain two load cells and, one rotational sensor. The two load cells measure the reactive loads during cable-based exercises.
5. Belt/Pulley Assembly provides the capability to perform cable-based exercises. It provides the interfaces between the exercise rope and the Arm Base Assembly via the Cable Arm Ropes to provide a load for the exercises. This is a mechanical assembly only.
6. Exercise Bench Assembly is an accessory that mounts to the platform and provides a surface for performing shoulder presses, bench presses, and other seated or lying exercises. Situps and other core exercises can be performed using the bench as well. It is folded up and stowed when not in use.
7. Heel Block Assembly is an accessory that mounts to the platform and allows the capability for performing heel-raise exercises. It is removed and stowed when not in use.

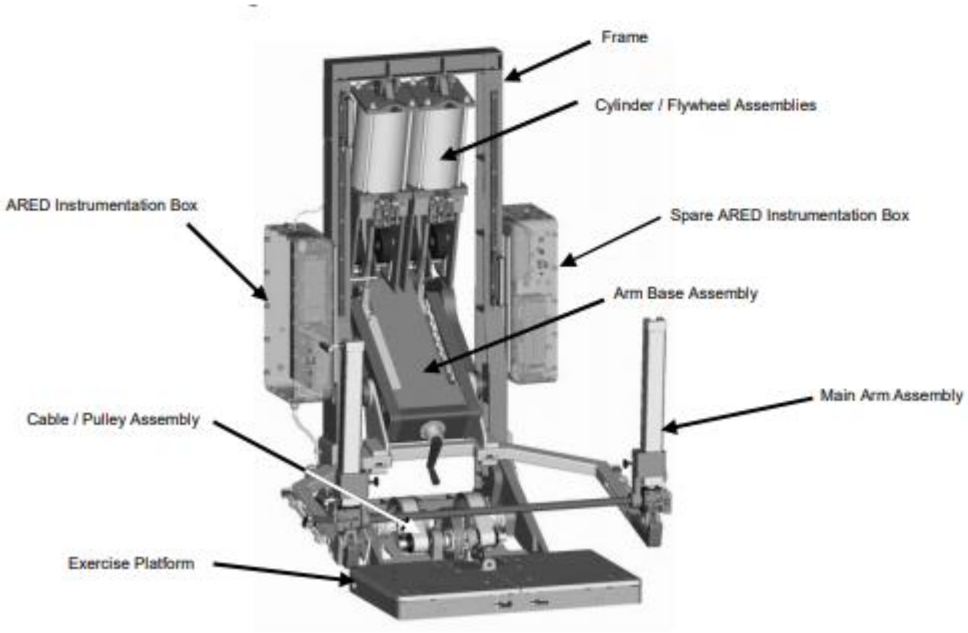


Figure 1. 2 Components of ARED [2]

The ARED operates in the following modes: Resistance is provided by the movement of the pistons within the vacuum of the cylinders. The piston rods are attached to an arm base assembly, which acts as a lever arm when the main arm assembly is moved.In addition, ARED is fitted with a second resistance mechanism. This mechanism is a flywheel assembly that rotates as the arm base assembly is moved. This function provides an inertial load which, when moved, mimics the inertial load of a free-weight.

The resistive load can be changed by turning a load adjustment handle that will move the attachment point of the piston rods, thereby changing the length of the lever arm. The lever is able to provide loads ranging from 0 to 600+ pounds. ARED can be configured to provide exercises using the lift bar or the exercise cable. Using the cable, the loads are limited to a maximum of 250 pounds.A major feature of ARED is the instrumentation system. This system includes triaxial force sensors located in the exercise platform that is able to record force in three dimensions. In addition, load sensors in the main lift arm and the arm base assembly measure unidirectional forces. The arm base assembly also has rotational sensors that record the range of motion of the arm.

1.2.Motion Analysis

Motion analysis is a technique which allows clinicians to quantify human movement patterns by measuring body movements, body mechanics and the activity of the muscles. It combines an examination of an individual’s physical structure with measurements of their function during activity. Moreover, motion analysis allows to collect quantitative information about the mechanics of the musculoskeletal system during the execution of a motor task to evaluate the complexities of that motion and is a valuable tool for specialists as they develop a treatment plan. Besides, the studies show, it allows to specialists to help children and adolescents maximize their physical abilities and achieve greater health and well-being as they grow [3].

In the areas of medicine, sports and kinesiology, human motion analysis have become an investigative and diagnostic tool which greatly decreases the time required to process the motion data. Hence, the professionals that include orthopedic physicians, physical therapists, Kinesiologists, and engineers review all of the motion data and makes treatment recommendations such as physical therapy, medication, bracing, and surgery. On the other hand, proper modification, manipulation, and control of the environment can help prevent injury, correct abnormality, and speed healing and rehabilitation.

Each analysis is composed of the clinical exam, electromyography (EMG), foot pressure measurement and camera recording. In clinical examinations, all measurements, age, height, weight, joint range of motion, muscle strength and tone, bony deformity and neurological assessment are taken to evaluate some specific terms and compare to data after examination. Developing a precise and noninvasive method for measuring the internal force within the human body for clinical and other purposes still remains a great challenge in the field of human biomechanics and motion analysis so therefore to correlate movement between the internal and external body, we need linkage technique which is an electromyogram (EMG). To obtain an EMG signal of muscles, ‘electrodes’ are taped to the skin, to measure the electrical activity that muscles produce as they are working and that sends these signals to the computer.

Foot pressure is required to measure forces which are acting on the body. Under gravity and other loads, human movement is achieved through a complex and highly coordinated mechanical interaction between bones, muscles, ligaments, and joints within the musculoskeletal system. Thus, these forces should be figured out with pressure sensitive force transducer which is force platform (or force plate). To calculate the movement patterns, the forces a body produces while walking is measured through special plates which are floor-mounted load transducers to measure the ground reaction forces (GRF) and moments, including the magnitude, direction, and location (called the center of pressure, COP). It provides distribution of forces in the area of contact on the surface of the plate to one resultant force vector, GRF, that is numerically and physically equivalent to all the applied forces. At the final, three orthogonal moments, three orthogonal components of force vectors are provided with respect to plate reference system origin. The range of sensitivity depends on the material that is produced. Two types of sensors are used in force platforms: strain gauges and piezoelectric crystals. The strain gauge models are less expensive and have good static capabilities, but it is not as sensitive as piezoelectric models which have a high-frequency response but requires specific electronics for measuring of static force. There is numerous kind of devices to capture force, but mainly working principle is all the same. Reaction force data are recorded while the patient is acting his/er motion on the force plates. Besides, a typical motion analysis laboratory has several cameras (video and/or infrared) placed around a walkway or a treadmill, which are linked to a computer. The cameras are used to capture and record the patient motion in real time as they move throughout in the specifically determined part of the lab. In the meanwhile, the motion is recorded with traces of highly reflective markers which are placed on patient's specific points where to be examined before the video. These special cameras measure the three-dimensional location of the reflective balls. There is some computer software that combines and synchronizes information from the cameras, the muscle sensors, and the force plates to produce a series of graphs for comparison and analysis. Data collected during motion analysis is always collected during barefoot walking, if possible. Sometimes, data is measured with and without braces or with different assistive devices such as walkers or crutches for comparison.

The information gathered from motion analysis is usually provided in a series of graphs showing joint angles, muscle activity, and force production. Based on the angle and the time delay between the original and reflected signal, triangulation of the marker in space is used. The software is used to create three-dimensional trajectories from these markers that are subsequently given identification labels. Preferably, a computer model is then used to compute joint angles from the relative marker positions of the labeled trajectories or simply by the basic calculations such as cosine law based on marker positions.

The most common method to collect kinematic data is motion capture system to record the motion of markers affixed to a moving subject and obtain coordinates of markers by digitizing the motion. The common imaging systems are video, digital video or charge-coupled devices. Generally, the multi-camera system is preferred not to miss any marker position. In this experiment, we used ELITE (BTS, Milano, Italy) camera system to capture the motion and Kistler (Model 9261, Kistler Instruments AG, Winterthur, Switzerland) force plates to gather pressure and force data which are acting on the body.

Nearly all engineers and academic staff in the field of sports kinesiology and biomechanics uses various motion analysis systems. Especially to analyze the motion is crucial for biomechanics research.

1.3.Exercise in micro-gravity conditions

The humans are constantly exposed to the universal force of gravitation, and thus to forces from within and surrounding the body. While gravity stabilizes the lower extremities in standing and provides friction for locomotion, it also places considerable stress on those body parts responsible for maintaining the upright position. Through the study of the interaction of these forces and their effects, the form, function, and motion of our bodies can be examined and the resulting knowledge applied to promote quality of life. Therefore, to truly understand our physical, chemical, and biological world, experimental activity in microgravity plays a significant role to discover body functions and systems because being in weightless conditions which cancel all gravitational effects and only forces that wanted to be explored can be evaluated easily.

In space conditions, a world in which we thought of only in three dimensions has turned out to have four. In fact, we must now add gravity to the complex list of factors and variables as we try to comprehend the world around us. Furthermore, the center of gravity is interchangeable on the earth's surface with a center of mass, is affected by reduced or large gravitational source and thus all parameters should be calculated by paying attention to this issue. Through this case, no longer can gravity be treated as Putting Space to work the world, all objects are accelerating more to the ground. When in Earth’s orbit, the gravitational pull of Earth is still there, but its effects are barely felt because an orbiting object is actually in free fall around Earth itself. Earth’s gravity keeps us circling around the planet in a condition that we commonly refer to as microgravity. Objects inside a spaceship seem to be “weightless” because they float inside the walls of the craft while they are falling with the ship around the curve of the planet. Hence, this case is most important for astronauts who do short or long-term space mission.

Biomedical research in space has the explicit and unique dual responsibility among the space sciences of pursuing both basic and applied research. Therefore, experiments in different gravity environments (microgravity especially) and the motion analysis have become a leading issue and measurement system in altered gravity conditions. In space conditions, we experience not the absence of gravity, but the absence of gravity’s effects [1]. Besides to obtain the systematic collection of kinematics data relative to the subject acting within either on earth or in the space environment, implementation of permanent motion analysis on board of Assembly of International Space Station is required but it is both technical and scientific challenge. Conversely, the ISS serves as a convenient platform on which we can deploy a variety of sensors to further our understanding in Earth and space science to the unique set of scientific researchers that were precluded in the 1G environment has performed mostly in ISS for several years to improve durability and continuity of astronauts' space mission.

1.4.A rationale for countermeasure Exercise

The lack of gravity's effects is perhaps the most dramatic feature of space flight and one that has caused significant changes in astronauts' life. Despite all efforts to provide before and after space mission and strict medical standards are being taken, there are inevitable results occur after the mission. The working environment for an astronaut is quite different from that of his or her Earth-based counterparts, and the crews carry the added stress of heavy responsibility and visibility during their missions.

The astronauts spend longer periods in space at greater distances from Earth, it will not always be practical to return a sick or injured crew member to the planet's surface for care. Neither will it be possible to fly a full complement of trained medical personnel with each mission. Applied research develops procedures and countermeasures that prevent or mitigate the undesirable effects of space flight on humans. The overriding goal of these activities provides human exploration and development of space by minimizing risks and optimizing crew safety, well-being, and performance. In so doing, it also expands our knowledge base of human physiology, resulting in new medical products and services that benefit life on Earth and in space. Certain physiological changes that occur in space also occur with aging. For instance, cardiovascular deconditioning, balance disorders, weakening bones and muscles, disturbed sleep patterns, and depressed immune responses are common to the astronauts and the elderly alike etc.

When in space, an astronauts' muscles and bones do not have to continually support the body against the pull of gravity. In some ways, this may mimic the results of a sedentary lifestyle, often caused by aging, paralysis, weakness, injury, or prolonged bed rest on Earth. This can cause a downward spiral in an individual's health over time, increasing susceptibility to bone fractures and slowing any recovery from injuries and other ailments.

The goal of exercise countermeasures is to maintain the health of crewmembers and their physical capacity to perform an intravehicular activity, extravehicular activity, and normal or emergency re-entry and egress procedures. Additional goals include reducing post-flight orthostatic intolerance, rehabilitation time, and the risk of musculoskeletal injury. In addition, the main aim is to increase the understanding of how resistance exercise in microgravity affects the body.

Spaceflight affects almost every aspect of the human body, including the heart, lungs, muscle, bones, immune system, and nerves. More specifically, astronauts experience a significant loss of both bone and muscle mass as a result of space flight. Upon return to Earth, astronauts often undergo a period of recovery, during which they regain things such as balance and coordination under the influence of gravity. Many of the physiological changes in astronauts actually resemble changes in the human body normally associated with aging here on Earth. For instance, in addition to losing mass in the microgravity environment, bones and muscle do not appear to heal normally in space. For astronauts, time spent in microgravity seems to result in a dissociation between their physical and chronological ages. By studying the changes in astronauts' bodies, scientists might play a role in developing a model for the consequences of getting older.

Skeletal muscle is highly adaptable and responding to stresses placed upon it. Being exposed to microgravity which is likely to disuse in Earth causes to a rapid decrease in muscle mass, change in muscle structure, contractile properties and muscle architecture [4] The change in the change in muscle structure is generally fiber-type specific depending on flight duration. Most human studies reported preferential atrophy of slow twitch fibers whose mechanical properties change towards the fast type [5]. Accordingly, the change in contractile properties which are a maximum isometric force, peak power, and maximum unloaded velocity decreases and increases respectively as a response to microgravity. In addition, the research [6] on the effect of space on the body support the view that due to the increased bone resorption in-flight mission, the bone formation either remains unchanged or decreases especially in longer duration. Spaceflight studies have shown quantitative effects which are including loss of bone mass and muscle mass, pronning to fiber specific muscle atrophy. The studies, in simulated or actual microgravity, human and animal postural muscles undergo substantial atrophy. After about 270 days, the muscle mass attains a constant value of about 70% of the initial one. [7]

Further research in this area may include exposure to microgravity besides bone loss and muscle atrophy, induces physiological changes in astronauts, reductions in aerobic and sensorimotor capacity [8]. They may affect the crewmember's ability to perform mission tasks. Exercise in space is used as a ‘countermeasure' to combat this physiological deconditioning, to keep crewmembers healthy and mitigate associated risks. In addition, a variety study of astronaut performance during and following space flight indicates that exposed to microgravity can cause neurosensorial, sensory-motor and musculoskeletal problems and changes in dynamics of human motion [9]. Based on post-flight observations of the physiological adaptation to µG and the large body of knowledge concerning the effects of different types of exercise on the cardiovascular and musculoskeletal systems, great progress has been made in in-flight exercise devices and exercise program designs, which, together, have become increasingly effective in countering µG-induced adaptation. Recent data from some ISS crewmembers, who have had access to the latest generation of devices and followed prescribed and intense training regimes during LDMs, show little or no change in bone mass and cardiovascular capacity, while the decreases in muscular force production are becoming progressively smaller.

Advanced exercise countermeasures hardware, crew equipment, and exercise routines are being developed to address these challenges, which will meet medical, vehicle, and habitat requirements and provide optimal and effective workouts in space.

Exercise Countermeasures Laboratory (ECL) at NASA Glenn Research Center (Cleveland, OH) is a ground-based testbed which provides high-fidelity weightlessness, lunar (1/6g) and Martian (1/3g) human-in-the-loop exercise simulations for developing exercise countermeasure devices, equipment, and exercise protocols for spaceflight, and quantifying the physiological demands of performing exercise in a shirt-sleeve environment.

This new ground-based simulation capability was developed to help address the detrimental physiological effects of space flight on the musculoskeletal system through improved exercise countermeasures systems, and to evaluate exercise countermeasures devices and prescriptions for space exploration.

Performing countermeasures which comprise intensive and resistive exercise provides a migitation of muscle atrophy and change in muscle architecture to normal limitations [10]. Moreover, resistive exercise is a countermeasure, which prevents the major muscle groups from weakening and lessens the bone loss. Resistive exercise helps astronauts maintain strength and endurance.

There are various types of resistive exercises which address different purposes such as being a strength, in balance, flexible or just being healthy. However, in the case to protect and maximize the muscle tone and strength, we need resistive exercises, deep, wide leg or back Squat based on the needs [11]. With body-weight exercises like squats or pushups, the muscles still have to work to control a weight, the difference is that it is the weight of the body. Strength or resistance training challenges the muscles with a stronger-than-usual counterforce. Using progressively heavier weights or increasing resistance makes muscles stronger. This kind of exercise increases muscle mass, tones muscles, and strengthens bones so helps to support and protect joints [12].

1.5.The squat exercise

The squat is one of the most frequently used exercises in the field of strength and conditioning. It has biomechanical and neuromuscular similarities to a wide range of athletic movements and thus is included as a core exercise in many sports routines designed to enhance athletic performance [13]. The squat primarily strengthens hip, thigh, and back musculature, which are very important muscles. Given that most activities of daily living necessitate the simultaneous coordinated interaction of numerous muscle groups, the squat is considered one of the best exercises for improving quality of life because of its ability to recruit multiple muscle groups in a single maneuver [14]. The squat is the main exercise type for advanced exercise countermeasures among all people due to its benefits of your full-body strength workout on both in lower and upper extremity with the amount of loads. It also is an integral component in the sports of competitive weightlifting and powerlifting and is widely regarded as a supreme test of lower-body strength. Benefits associated with squat performance are not limited to the athletic population. Given that most activities of daily living necessitate the simultaneous coordinated interaction of numerous muscle groups, the squat is considered one of the best exercises for improving quality of life because of its ability to recruit multiple muscle groups in a single maneuver. The squat also is becoming increasingly popular in clinical settings as a means to strengthen lower-body muscles and connective tissue after joint-related injury. It has been used extensively for the therapeutic treatment of ligament lesions, patellofemoral dysfunctions, total joint replacement, and ankle instability.

The performance of the dynamic squat begins with the lifter in an upright position, knees, and hips fully extended. The lifter then squats down by flexing at the hip, knee, and ankle joints. When the desired squat depth is achieved, the lifter reverses direction and ascends back to the upright position. In the study, it is monitored that This dynamically recruits most of the lower-body musculature, including the quadriceps femoris, hip extensors, hip adductors, hip abductors, and triceps surae [15]. In addition, significant isometric activity is required by a wide range of supporting muscles (including the abdominals, erector spinae, trapezius, rhomboids, and many others) to facilitate postural stabilization of the trunk. In the study Solomonow et al, it is estimated that over 200 muscles are activated during the squat performance. Squats can be performed at a variety of depths, generally measured by the degree of flexion at the knee. Strength coaches often categorize squats into 3 basic groupings: partial squats (40 knee angle), half squats (70 to 100), and deep squats (greater than 100). Squats can be performed using just one's body weight or with an external load. Squat depth should be consistent with the goals and abilities of the individual [16].

There are several types similar or slightly different from squat according to needs such as wide leg squat, single leg squat and deadlift. This study will introduce all these four types of resistive exercises.

Regular squat with additional load is one common exercise shown to improve lower limb strength and muscular power. On the basis of the evidence currently available, It has been demonstrated that lower-body strength and power methods, such as bilateral squat offers a high level of utility for all athletic populations [17]. It consists of the movement which begins from a standing position with the feet hip-width apart moving the hips back, bending the knees and hips to lower the torso, then returning to the upright position.

The wide leg squat mimics all squatting movement similarly, but with the wider feet distance with 45 degrees, toes pointing out than hip-distance apart (about three to four feet). A wider stance squat is preferable for those seeking optimal development of the hip adductors and hip extensors.

The single leg squat is known as also One-Legged Squat, an excellent functional bodyweight training exercise that will develop leg strength, flexibility, improve balance. Unilateral exercises, in particular, the single-leg (SL) squat, have typically been used for movement screening purposes; however, it is an effective supplementary leg strength exercise as it involves an increased balance demand [18]. The only difference from regular squat as a movement is one leg extended straight in front of and with other leg squatting down-up as far as possible keeping elevated leg off the floor by preserving balance [19].

Another resistive exercise apart from the squat is deadlift. The deadlift is a multijoint resistance exercise that is performed in a variety of training settings. The exercise requires the lifter to grasp a barbell at the mid-shank level in a squat position and elevate the load by extending the lower back, hip, knee, and ankle joints. There is an eccentric (lowering of the weight) phase followed by the concentric (lifting of the weight) phase. The main feature that makes deadlift different from squat is sitting back instead of sitting down. The movement comes from the hips, not from the knees [20]. At the bottom of the movement, the hip joint was flexed by the greatest amount, followed by the knee, torso, and ankle. The deadlift is most frequently used to develop maximum strength based on the hypothesis that heavy loads lifted will generate large muscular forces and stimulate adaptation. A number of studies have quantified biomechanical variables during the deadlift [21]. Results have confirmed that large muscular moments can be produced with the greatest values recorded at the hip, followed by the lumbar spine, ankle, and knee [22].

Studies that included linked-segment models reported net joint forces ranging from approximately 1,450-1,550 N at the hip, knee, and ankle joints for adolescent powerlifters during competition. Studies that have included linked-segment models designed to estimate forces on the lumbar spine have reported extremely large disk compression forces during the deadlift [22].

To understand well the effect of resistive exercises in each level of body and joint is essential to plan a more human-specific exercise program.

1.5.1. Effect of Squat on the lower limb joints

1.5.1.1. Ankle Joint

The ankle complex as part of a comprehensive analysis of joint activity while squatting. The ankle complex is comprised of joints whose actions taking place at these joints include dorsiflexion/plantar flexion and eversion/inversion, as well as a small amount of abduction and adduction. As you lower into a squat, shins tilt slightly, an action of the ankle joint called dorsiflexion. When you stand up, your shins move back as your ankles plantar flex [23].

During the squat performance, y-the ankle complex contributes significant support and aids in power generation during the squat performance. A high degree of mobility at the ankle is required to facilitate balance and control in both the ascent and descent of the squat. Mostly in studies, the plantar flexion of the ankle is assumed as a movement to determine the moment of force at ankle joint level.

It is suggested that significant strength and mobility is required at the ankle for proper squat performance. Feet should be positioned in a comfortable stance that allows the knees to move in line with the toes [24].

1.5.1.2.Knee Joint

The knee joints and their associated musculature also work during a squat. As torso goes downward, the knees are flexed, lengthening the quadriceps muscles on the front of the thigh. When stand up position is provided, the quadriceps contract allows to extend the knee joint. Muscle activity generally progressively increased as the knees flexed and decreased as the knees extended, which supports the body performing the parallel squat over the half squat.

The knee is a hinge-type joint, but with a little twist to lock it into full extension. Instead of a fixed axis, it's a complicated movement consisting of gliding and rotation in such a fashion that the articulating surfaces are always changing. Hence, the axis is always changing. The knee joint consists of the tibiofemoral, which carries out sagittal plane movement throughout a range of motion of 0 to approximately 160 of flexion [25]. A small amount of axial rotation is also present at the joint during dynamic movement, with the femur rotating laterally during flexion and medially during extension with respect to the tibia. The knee is supported by an array of ligaments and cartilage. Whereas the knee ligaments are the main static stabilizers of the joint, the knee musculature assumes a dominant role in dynamic joint stabilization. During the squat, to talk about it briefly the primary muscles acting on the knee, which carry out concentric knee extension, as well as eccentrically resisting knee flexion. Moreover, there are technically antagonists muscles, opposing knee extensor moments. To determine the moment of force at the level of the knee, relative angle (angle between shank and thigh segment) of the knee joint is considered.

Given the fact that shear forces are increased as the knees move past the toes during the downward phase of the squat, attempts should be made to avoid significant forward knee translation on the descent.

1.5.1.3.Hip Joint

The hip joint and hip muscles are a primary focus of the squat [26]. As you descend, your hip joints flex, stretches the hip extensor muscles. The hip joints also abduct slightly as the thighs wide apart, lengthening the adductor muscles of the inner thighs. The adductors aid the hip extensors by drawing the thighs toward each other. The hip is a ball-and-socket joint, comprising the articulation between the head of the femur and the acetabulum of the os coxae. It is freely mobile in all three planes of movement, carrying out flexion and extension in the sagittal plane, abduction, and adduction in the frontal plane, and internal/external rotation and horizontal abduction/adduction in the transverse plane. During the squat, hip torques increase in conjunction with increases in hip flexion, with maximal torque occurring near the bottom phase of movement [27].

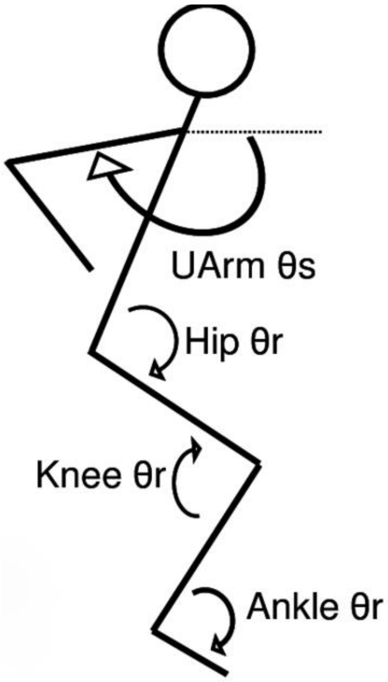


Figure 1. 5 Joint used in moments calculation [28]

Given the close relationship between the movement at the hips, pelvis, and lumbar spine during dynamic squatting, hip mobility is extremely important for proper squat performance, especially at higher flexion angles. Poor joint mobility can lead to greater forward lean and thus increased spinal shear. Although some lifters attempt to increase hip flexion by using posterior pelvic movement during squat descent, this can heighten lumbar stress and is thus not advisable.

1.5.2. Effect of load position

Weighted squats can be performed by the external load placed in a variety of positions. There are typically two different bar positions used when performing the back-squat; the traditional 'high-bar' back-squat (HBBS) and the 'low-bar' back-squat (LBBS). Different movement strategies are employed to ensure that the center-of-mass remains in the base-of-support for balance during the execution of these lifts [29]. These movement strategies manifest as differences in 1) joint angles, 2) vertical ground reaction forces and, 3) the activity of key muscles. The most studied variations are a low bar back squats with the bar slightly below the level of the acromion, high bar back squats with the bar slightly above the level of the acromion, and barbell front squats with the bar held in front of the chest at the clavicle [30]. Because of a greater forward inclination of the trunk, the low bar position typical of powerlifters has been shown to produce greater hip extensor torque and less knee extensor torque compared with high bar squat typical of weightlifters.

1.6.Kinematics and Kinetics of Human Movement

One of the primary goals of biomechanics research is to quantify the patterns of force produced by the muscles, ligaments, and bones. To understand well the forces which are acting on the body, first, we need to illustrate all the loading levels, parameters, and forces. Utilizing from segment modeling, and computer graphics-based anatomical modeling to understand the kinetics of human movement is a useful approach to estimating loadings and forces.

Kinetics, a branch of classical mechanics that concerns the effect of forces and torques on the motion of bodies having mass. Usually, the term kinetics are used the nearly synonymous name ‘dynamics’ to the classical mechanics of moving bodies. To analyze the human movement system, we need to understand the dynamics of structure which need to some predetermined inputs such as position, velocity, and acceleration which come from a kinematic analysis or inverse kinematics calculation by the equation of motion. Kinematics is a branch of classical mechanics that describes the motion of points, bodies (objects), and systems of bodies (groups of objects) without considering the mass or the forces that caused the motion [31]. In addition, kinematics, as a field of study, is often referred to as the "geometry of motion" and is occasionally seen as a branch of mathematics and thus provides inputs for Dynamics system [32].

Human movement is achieved by a complex and highly coordinated mechanical interaction between bones, muscles, ligaments, and joints within the musculoskeletal system under the control of the nervous system. To sense the movement, first, we need to figure out the kinematics and followed by kinetics. The Kinematics data, such as both linear and angular position, velocity, and acceleration are required to evaluate motion which is study of joint motion is used to obtain motion data and joint angles from specialized cameras connected to a computer which can figure out at least planar motion of reflective markers aligned on the body parts where would like to be examined. All movements and changes in movements are generated from the action of forces, both internal and external. Muscles generate tensile forces and apply moments at joints with short lever arms in order to provide static and dynamic stability of the body under gravitational and other loads while regularly performing precise limb control [33]. Any injury or lesion of any individual elements of the musculoskeletal system, will change the mechanical interaction and cause degradation, instability or disability of movement.

In the biomechanical point of view, it is essential to have a model and accomplish the techniques of motion analysis for quantitative data. It includes measuring human motion and external loads, developing multi-dimensional (2D or 3D) computer graphics-based biomechanical models based on different tracking or reconstructing techniques, calculating internal forces and validating the results. A validated biomechanical model can be applied to the simulation of various movements and surgical procedures.

In the field of kinetics, force and their measurement are clarified by principles of Newton laws and Euler equations. The force represents the action of one body to another so it has specific effects on the rigid and deformable body when we consider internal forces within a tissue level and external forces applied to or by humans. In addition the in the analyses of angular motion, we consider that force is distributed over an area of contact which is known as pressure. The kinetics analyses concern that external forces and the pressure applied through direct contact with the ground or object. In the movement analyses, the major force is ground reaction force.

1.7.Inverse Dynamics

The inverse dynamic is the specialized branch of mechanics that bridges the areas of kinematics and kinetics. It is the process by which forces and moments of force are indirectly determined from the kinematics and inertial properties of moving bodies. In principle, inverse dynamics also apply to stationary bodies, but usually, it is applied to bodies in motion (Winter et al., 1990) [34].

A change in the force acting on an object is necessary for moving it from a stationary position or for changing its velocity. The amount of change in the velocity of an object depends on the magnitude and direction of the applied force. Newton’s laws of motion give a clear relationship between the changing force and the resultant change in movement, and this is applicable to all forms of movement, including human locomotion.

Inverse dynamics, although incapable of quantifying the forces in specific anatomical structures, is able to measure the net effect of all of the internal forces and moments of force acting across several joints. In this way, what total forces and moments are necessary to create the motion and quantify both the internal and external work done at each joint can be inferred. To evaluate the force exerted by a muscle, one of the indirect method using readily available kinematics and anthropometric data which are the disciple concerned with the measurement of the physical characteristics of humans is link-segment modeling. After camera, the markers are placed on the subject with respect to required parts, for instance, to lower extremity and/or upper extremity.

The process starts at a terminal segment, such as the foot or hand, where the forces at one end of the segment are known or zero. They are zero when the segment is not in contact with the environment or another object. Furthermore, the foot is assumed to be a "rigid body," although some researchers have modeled it as having two segments (Cronin and Robertson 2000; Stefanyshyn and Nigg 1998). A rigid body is an object that has no moving parts and cannot be deformed. This state implies that its inertial properties such as mass, the center of gravity and mass distribution are fixed values.

To complete the inverse dynamic process for the foot, every anatomical force, including ligament and bone-on-bone (actually, cartilaginous) forces, must be transferred to the common axis at the ankle, only forces that act across the ankle are included in this process. Internal forces that originate and terminate within the foot are excluded, as are external forces in contact with the sole of the foot. They contend that each joint has two single, equivalent muscles that produce the net moments of force about each joint, one for flexion and the other for extension depending on the joint’s anatomy. The ankle forces and moments of force are summed to produce a single force and moment of force, called the net force and net moment of force, respectively. In addition, the resultant force and moment of force of a rigid body are the sums of all forces and moments acting on the body.

Besides, the term moment of force is often called torque in the scientific literature. In the biomechanics literature, the torque that is usually considered a moment of force that causes rotation about the longitudinal axis of an object so torque and moment of force are used interchangeably.

These sums are not the same as the net force and moment of force just defined. The resultant force and moment of force concern Newton’s first and second laws. In this process, we use body kinematics and anthropometric parameters to calculate the net forces and moments at the joints. This process employs three important principles: Newton’s second law (F Æ = maÆ Â), the principle of superposition, and an engineering technique known as the method of sections. The principle of superposition holds that in a system with multiple factors (i.e., forces and moments), given certain conditions, we can either sum the effects of multiple factors or treat them independently.

As suggested in the literature, the field of kinetics is underlined by three Newton's law [34]. However, the dynamic principle is derived from mostly Newton's first and second laws. First law describes how the body moves while the absence of an external force which is known as ‘law of inertia'. In the second law, an external force causes the body to accelerate as the magnitude of force and direction of the force which is known as ‘law of acceleration'. The formulae are briefly shown in the (1) and (2). The third and most significant law which is ‘law of reaction' specifies that when one body applies a force to another body, the second body applies force exactly same magnitude but in the opposite direction as a reaction force.

In principle, all forces acting on an object create a rotation, the Moment of a force, that is affected in proportion to the distance by which the applied force and mass center are out of line. Given a 2-D Free Body Diagram, FBD, the process is to employ Newton’s second law in the horizontal, vertical, and rotational directions:

$$\sum F_x = ma_x \tag{1}$$

$$\sum F_y = ma_y \tag{2}$$

$$\sum M = I\alpha \tag{3}$$

The mass, m, and moment of inertia, I, for the object in question are determined beforehand. The linear and angular accelerations are determined from camera data. The sum of the forces/moments on the left side of each equation (i.e., each term) can combine many forces/moments, but it should contain only one unknown, a net force or moment, to solve for phenomena.

To define the 2-D movement of the human joint system, the engineering term general plane motion is used. In this case, an object has three degrees of freedom (DoF): two linear positions and an angular position. Through x-axes and y-axes the translations and through z-axis the rotation is considered. To determine the kinetics of such situations, the fundamental principle is that the three DoF are treated independently. Accelerations in the horizontal and vertical directions are measured, and therefore the forces can be able to determine in the horizontal and vertical axes. However, there is also an angular acceleration proportional to the product of the force, F, and the distance, d, between its line of action and the center of mass. a force causes a body’s center of mass to accelerate in the same direction as that force. A force does not cause a body to rotate; only the moment of a force causes a body to rotate.

To go deeper into parameters that we need to solve inverse dynamics problem, it is significant to utilize from the displacement of marker positions, by the process of mathematical differentiation, linear kinematics data such as velocity and acceleration has to be found. To calculate force data of each segment, we need also linear acceleration. All these three kinematics variables give different looks about understanding what kind of movement, it is or how motion has been affected by interventions. Similarly, angular kinematics variables are obtained by differential calculus or integral calculus. Nevertheless, in the case of angular kinematics, it is essential to define the position measures are the segment (absolute) angles which concern the angular position and orientation and the relative (joint) angles that concern the angle between two segments of the body. For the absolute angles, at least two points (they are usually markers which are on joint centers) must be quantified and the right-hand rule underlies the indication of the sign of rotations.

Based on the law of gravitation, gravitational force has named as a weight which obtained by multiplication of mass and its acceleration. The person is applying a force to the earth equal to his weight, while the earth is applying an equal and opposite force on the person. This is GRF that is pointing upward in every simulation. Hence basically there are two vertical forces acting on body those are weight (downward) and GRF (upward). The 3D direction of the GRF depends on how the person applies to force on the ground. Through the friction force which is opposed and parallel to relative motion provides other components of GRF that are anterior/posterior(A/P) and medial/lateral (M/L).

Inverse dynamics problems often require careful bookkeeping of positive and negative signs. However, in most cases we calculate moments about the mass center; there, we can neglect the reaction force and gravity terms because their moment arms are zero. Moreover, In the biomechanical analysis, resultant force concept is used because the force consists of vectors and if there is an external force or other contact points, different vectors are formed. However, to calculate simply and exactly the interactions even in force or in other parameters, we need the resultant outcome.

In the method of sections, the basic idea is to imagine cutting a mechanical system into components and determining the interactions between them. To visualize each force in each body part there is a diagram which is called free-body diagram. This method helps to remind all forces, moments of force and geometry of mechanical systems. Mostly convention is that a counterclockwise moment is positive, also called the right-hand rule. Coordinate system axes on FBD, establish their positive force directions.

For example, usually, the human lower extremity is analyzed as a thigh, leg, and foot one-by-one. Then, via Newton's second law, we can determine the forces acting on the joints by using measured values for the GRFs and the acceleration and mass of each segment. This process called the linked-segment or iterative Newton-Euler method. It is essential, to begin with, kinetic analysis of single objects in 2-D, then demonstrate how to analyze the kinetics of a joint via the method of sections.

In biomechanics, the terms such as flexion, extension or hyperextension are used to define the positive or negative rotation of joints. To determine the joint angles, a minimum of three coordinates or two absolute angles is required. When defining the joint motions, it should be taken into consideration that adjacent joints may have different directions for the same type of motion. For instance, to have flexion of the knee provides positive rotation for the global coordinate system, GCS, but at the flexion of hip provides negative rotation. Other data which are required for kinematics are segment parameters such as segment mass, segment moment of inertia. The segment mass varies from a range of ages because of the length of segments so, in literature, we have standard values for a middle-aged male but for young adult subjects we can use a simple equation which is represented by Zatsiorsky et al. [35].

$$m_s=P_s m_{total} \tag{4}$$

where m_s is segment mass, P_s is mass proportion and m_{total} is total body mass. The mass proportion varies for each segment.

$$I=1/3mL^2 \tag{5}$$

where I is a moment of Inertia, m is mass of the segment, L is the total length of that segment.

Moreover, segments’ moment of inertia which is detracted in formula (5) is needed for whenever rotational motion is investigated. It is computed by the values segment mass and distance length to center of mass. An indirect method has used that calculation of Radius of gyration which indicates the distance that represents how far the mass of body from an axis of rotation. By multiplying gyration and square of the mass of that rigid segment, the value for each segment moment of inertia is calculated. Indeed, the way of computation of all parameters varies from 2D to 3D approaches.

In 3D analyses, we are dealing with transformations of coordinates, computation of angular and linear parameters and the significant difference is the computation of moment of inertia. It is crucial to transforming GCS to the laboratory coordinate system (LBS) which done by linear and rotational transformations.

1.8.Study Aim

The goal of the proposed study is to quantify the joint load obtained during exercise on ARED and suggest the most efficient and effective exercise program for the maintenance of muscle function by evaluating optimal load level in microgravity.

Given that skeletal muscles undergo reduced mass, strength, and endurance in flight, there is a possibility the crew will be physically unable to perform mission tasks. The device must protect crew fitness current exercise hardware on the International Space Station. Therefore, the ARED was developed so needed to determine the load using the device in weightlessness.

1.9.Outline

In the following sections, the microgravity effect and countermeasure exercises will be presented. As a countermeasure exercise, regular squat, wide leg squat, Deadlift and single leg squats were done with the aim of assessing the optimal load level to preserve the strength of muscles. All the measurements were acquired by a motion capture system and force plates briefly described in methods, in the data collection stage. After that, the study will continue with the calculation of force and moment of the joint in lower extremity with evaluations of kinematics and inverse dynamic principle in data processing part. Then, the focus will be given to calculation and evaluation of the cost function and optimal load. Particularly in this study, the optimal load was assessed by considering all joints so in final, unique load was obtained. In the result section, all moments of joints and the cost function with the load range from 0 to 100 kg and load range from 60 to 80 kg respectively will be shown. The discussion part will present the limitations and assumptions that need to have complete data and demonstrate the possible errors. Finally, in conclusion, part the whole work summarized, underlining the achievements and some suggestions are taken place.

2. MATERIALS AND METHODS

2.1. Experimental setup

In this chapter, the fundamental devices which are used in data collection and processing will be described.

2.1.1. Motion capture system

To observe the human motion and analyze it, we need a quantitative motion analyzer to capture and evaluate the parameters which help to understand motion. Fundamentally, two different motion capture systems (passive or active markers) are used under different conditions; the largest instrumental error about the reconstruction of angles [36].On one hand, analyzing the human movement has been more challenging in the altered gravity condition which provides unique experimental conditions for monitoring every aspect of movement or human systems. To analyze human motion, it was essential to give importance to the development of the hardware of a new automatic motion analyzer for space applications. ELITE-S2 (Elaboratore DI Immagini Televisive-Space qualified version 2) was designed by the Italian Space Agency for the European Physiology Modules (EPM) as a quantitative 3D biomechanical motion analyzer system in weightless conditions. It is an optoelectronic system which has been used for motion analysis in space due to the high intrinsic accuracy and flexibility. With respect to subject calibrated devices, they are designed in order to take measures within a suitable calibrated working volume, without making contact with the subject or constraining movements in any other way. ELITE-S2 provides several facilities such as motion analysis based on passive markers which means full movement, freedom without cable connections also with an unlimited number of markers and real-time image processing for marker shape recognition to reach a higher accuracy with reduced marker dimension.

ELITE-S2 provides measurement of three- dimensional coordinates of body landmarks, with the reconstruction of trajectories on the ground for kinematics analysis.

Retro-reflective markers are placed on the subject in correspondence with anatomic landmarks, according to the specific protocol [37] and illuminated by IR sources are applied to selected body landmarks (within the calibrated working volume). Markers movement is captured and computed in real time by the image processing devices (optics, camera, and dedicated processing electronics). In other words, the positions of markers are detected by analyzing images from video cameras placed around the working area. The movement data are delivered to an acquisition and collection device. The collected data are stored in the ELITE-S2 system. In some cases, the acquired data can be visualized for real-time 3D representation of the onboard computer. 3D calibration is required for on-orbit operations. This process involves the computation of 3D coordinates of each marker within the working volume by its 2D coordinates on each camera sensor. The calibration on orbit has been completely redesigned in order to reduce the time requested and to ensure the required accuracy. Moreover, analog signals are also acquired and collected by dedicated electronics for multifactorial analysis. Acquisition of Analog channels can be synchronized with the motion data, in the sense that the system provides the possibility of correlating the acquisition time from the two sources. Other devices control the system functioning by monitoring status and housekeeping, interpreting commands coming from the different sources and by executing the necessary and pre-programmed corrective actions.

Although previous experiences have demonstrated the feasibility of the use of optoelectronic motion analyzer onboard orbital modules, there are several factors affecting the reliability and accuracy of optoelectronic motion analysis in space. In general, operators (astronauts) have not been experts in motion analysis, in order to reduce crew time, operators are required to perform experiments on themselves, thus requiring self-marking procedures, environmental and time schedule restrictions limit the experimental resources and operating in microgravity conditions cause difficulties even in simple set-up operations.

A requirement for ELITE-S2 is to be capable of processing and displaying in real time 3D trajectories, including marker labeling and 3D reconstruction as well as a graphic representation. The real-time mode will provide the subject with on-line feedback when experimental setup is particularly critical and difficult.

Another critical aspect concerning the on-orbit operations consists of the markers positioning on the required body landmarks. This is strongly protocol-dependent, but in any case has to face the limitation that, in order to reduce crew time, operators are required to perform experiments on themselves, thus requiring self-marking procedures.

2.1.2. Exercises

To conduct this experiment, four different resistive exercises were performed under normal gravity condition and fixed load; regular squat, wide leg squat, deadlift and single leg squat respectively for 3 sessions and 5 reps.

2.1.3. Data Collection

The data collection was carried out on a male astronaut subject for two different sessions, pre-flight and post-flight with a BTS force platform with lasting approximately 1-hour exercises.

The kinematic data were acquired by two motion capture system; ground-based ELITE-S2 and 12 cameras BTS Smart-D motion capture system with 100 Hz sampling frequency. A study has been conducted within the ELITE-S2 program, the motion data were acquired by 12 camera motion capture system (BTS Bioengineering S.p.A., Milan, Italy) and ground reaction forces measured by two force plates (Model 9261, Kistler Instruments AG, Winterthur, Switzerland) with 100 Hz sampling frequency for both feet.

Twenty–one retro reflective surface markers were placed over bony landmarks: foot toe (first meteatarsal head), lateral side foot, calcaneous, lateral malleolus; a cluster of three marker attached to the shank, one for the mediolateral knee (femoral lateral epycondile), a cluster of three markers for the thigh, one for trochanter, one for the Asis (Anterior Superior Iliac Spine), Psis (Posterior Superior iliac Spine), the iliac Crest and the Sacrum; a cluster of four markers for the lateral side of the trunk and one for Scapula (as indicated by the Davis protocol; Davis et al. 1991).

The force plates were put side by side on the ARED foot plate area that enables to get different force measurements from independent force plates to ensure the reliability. To ensure the reference system between force data and a motion capture system, 3 markers were placed onto the shoe.

In addition, the study was considered toward the most critical aspect in such area the correct repositioning of the markers from trial to trial. Therefore, for the trials, the markers were placed onto a spandex suit instead of onto skin to avoid from skin artifacts as indicated in the study conducted by Leradini et al.[38]

In principle, the ARED vacuum cylinder loads were submitted based on the maximum load that subject could perform 12 repetitions of the squat. However, in this experiment, the load was always fixed at 120 lbs along all the sessions and by fixed order of exercises; regular squat, wide leg squat, deadlift, single leg squat. After a gentle warm-up session exercises, each resistive exercise was performed for 5 reps. A cycle of squat includes from the most extended to most flexed posture and returning back to most extended posture. However, the exercise for deadlift was started from bending down with grasping the barbell then movement sequences as like squat. The subject performed exercises with a fixed load bar placed on his shoulders.

2.1.4. Data Processing

To process the data from ELITE-S2, SMART software was used not only to track but also to process the raw data. BTS SMART-Analyzer is the software tool for the biomechanical analysis of movement with the integration of 3D, video and analog kinematic data coming from force platforms, electromyography or other devices. [39] The software allows to build a calculation scheme that generates all the data necessary for a complete analysis of the motor gesture.

The data which are obtained from ELITE S2 was stored in an ESD file which contains marker trajectories in three dimensions. To acquire all quantitative variables which are necessary to evaluate joint and muscle features, the sequence of marker positions were needed to adapt to SMART Analyzer virtual platform. To transfer data, a model, figure 3.1, was built with respect to number and the position of each marker to mimic the subject in SMART Analyzer. The rigid reconstructed bodies were foot, shank, thigh, pelvis, and trunk. The marker names and correlated position were assigned to the model.

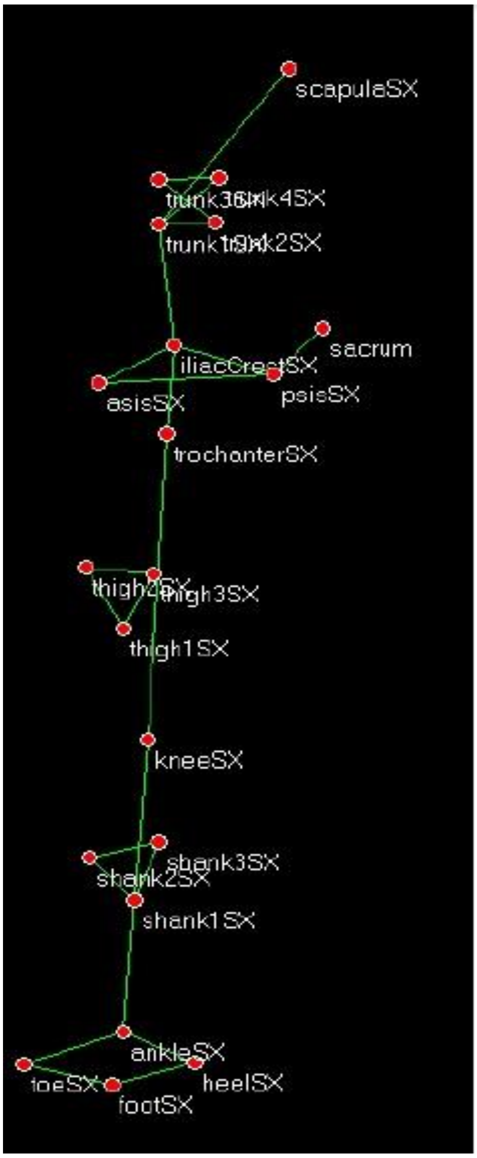


Figure 2. 1 Constructed model to represent the body

Furthermore, unassigned and disconnected motion data was tracked in the SMART Tracker software for each surface marker separately which are given in figure 3.2. Then after tracking was completed, tracked marker trajectories were assigned to the associated marker and after all, markers were tracked, the file was saved as a TDF file that is a suitable file for being input to SMART Analyzer. This process was repeated for each resistive exercise file.

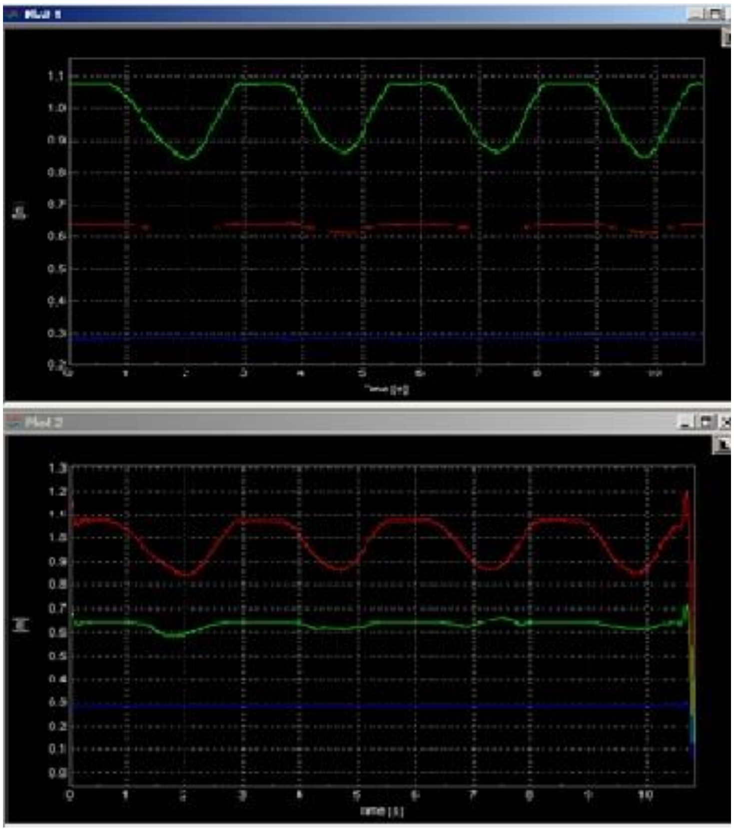


Figure 2. 2 The angle data of hip, knee, and ankle joint before and after tracking

In the processing part, the SMART Analyzer was used. To operate data in it, a protocol was developed (figure 3.3), consisting of graphical blocks and allowing to process relevant data.

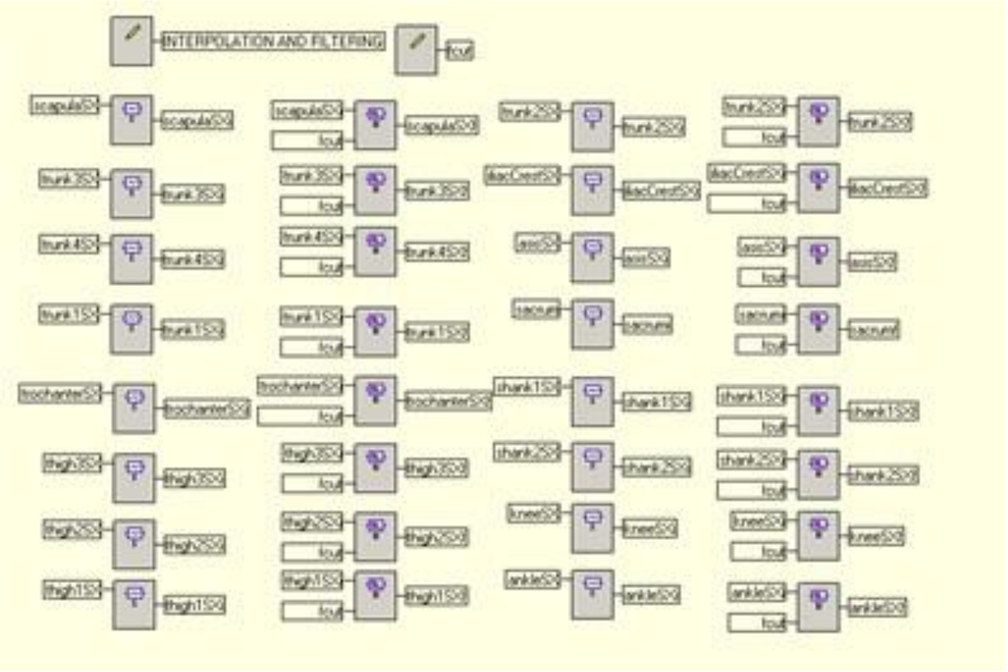


Figure 2. 3 A representation of graphical blocks for interpolation and filtering operations in SMART Analyzer

The first operation was filtering. The data were filtered via Butterworth low pass filter with cutoff frequency of 5 Hz. Moreover, to obtain a mean cycle of each trial for one resistive exercise, the onset and offset of squat cycles in different files was determined based on the markers attached at the hip joint. End of this operation, only 1 global cycle was created for each exercise type. Indeed, working on global cycle permits to process more than 1 file at the same time in a mean way with time normalization. Thanks to graphical blocks which are offered by the program, linear and angular acceleration quantities were calculated gradually for each time frame in global data. Likewise, the center of mass data of each segment was calculated via block operators, according to marker position of joints and anthropometric coefficients in the literature which is briefly mentioned in Table 3.1. In addition, GRF data measured via ARED force plates were taken as a unique mean value from two force plates and was correlated with squat cycles. All the steps were performed for each type of resistance exercise files and outputs were obtained as a text file in global data.

Table 1 Body segment coefficients

Segment	$R_{proximal}$*	**Relative weight****	$m_{segment}$ **(kg)**
Foot	0.5	0.0145	1.2
Shank	0.433	0.0465	3.567
Thigh	0.433	0.1	8.4214

*location of the center of gravity from the proximal or distal end of the segment as a proportion of segment's length.

** segment mass proportion of total body mass, equal to the m_{total}/ $m_{segment}$ ratio.

Eventually, to extract the GRF signal, TTL signal was considered. By triggering the signal generated at 200 Hz as shown in figure 3.4 from ELITE-S2 to force plate, the GRF signal is synchronized with TTL signal between 0-5V at 250 Hz.

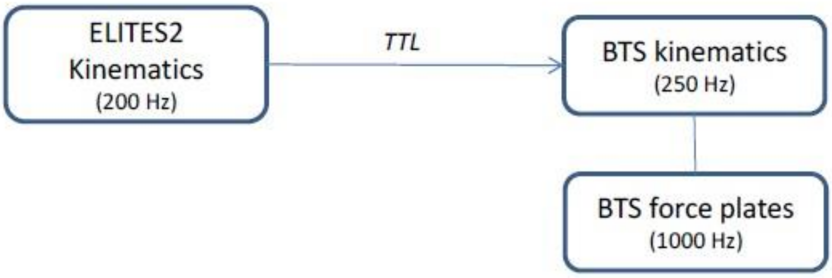


Figure 2. 4 Sync TTL signal generated by ELITES2 and read out by the BTS system to correlate GRF data

Each ELITE-S2 frame (5 ms) consisted of 2 ms at 0 V and 3 ms at 5V. As shown in figure 3.5, each block represents a different correlated GRF data, such as 1st and 2nd blocks belong to a regular squat, 3rd and 4th blocks belong to wide squat. The extracting and submitting of GRF data for each exercise file was conducted in the SMART analyzer protocol. On the other hand, other significant data, the CoPs, are literature estimated with respect to size and GRF data because the distribution of pressure contents was spread in a wide range in the captured area so it was not a reliable data to use in force and moment of force of each joint calculation.

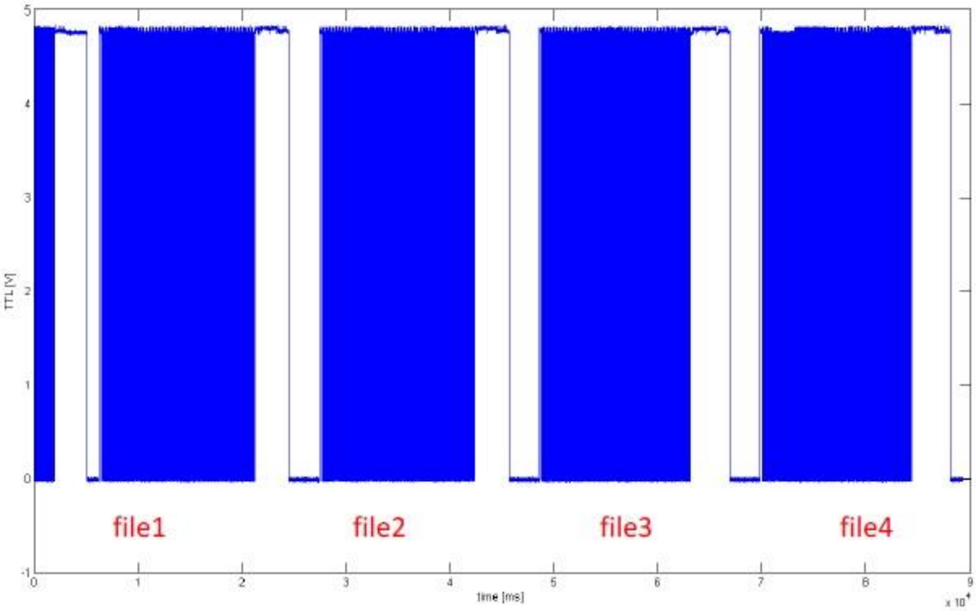


Figure 2. 5 TTL signal acquired by ELITE-S2

The calculation of force and moment of force for each joint was done both in Excel and Matlab software. The principal knowledge of kinetics and inverse Dynamics based on Newton Biomechanics that was briefly explained in the introduction, the quasi-static solution was used to calculate the sagittal moments and force in the ankle, knee and the hip. The 2D model was generated based on the method of section which is shown in figure 2.6 to evaluate force and moment of each body segment separately. The inertial parameters of each segment were calculated with respect to the formula given (4) in an inverse dynamics chapter from subject-specific anthropometric data.

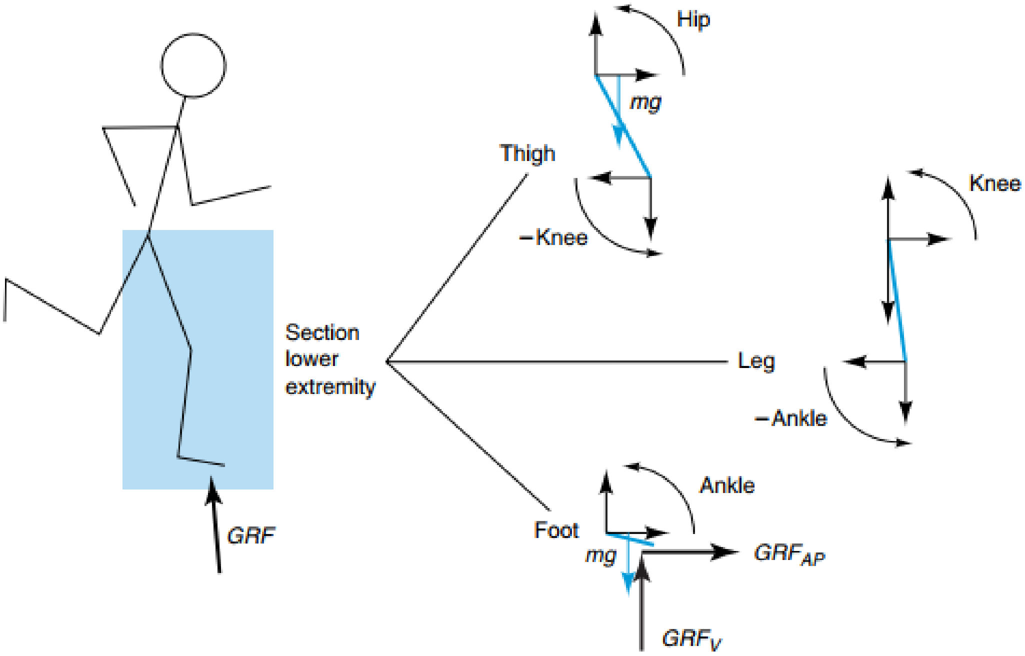


Figure 2. 6 Method of section for lower extremity [34]

Initially, all assumptions and calculations to obtain force and moment were formulated for Earth's gravity condition (g=9.81 m/s^2) under a fixed load (L=54 kg) and then for microgravity condition (g=0) under varying load levels starting from 0 to 100 kg.

In Matlab, to evaluate force and moment of force for each joint, system of Newton's equations was solved for regular squat, wide leg squat, deadlift and single leg squat. Resulting moments were normalized to the division of BW (body weight).

As a technique, the system of linear equations method which is shown in the appendix was used to get the force, moment and GRF data respectively in Matlab. Although experimental GRF data was valid, estimated GRF values for each frame were needed to mimic the exercise in microgravity conditions. In microgravity, the gravitational force on the body segment is null, but for applying the load, we need to estimate a suitable GRF data which represents the reaction force only based on exercise with the load under microgravity condition. The method requires the same number of equations and variables to be found. For every frame, force, a moment of each joint and GRF values were calculated. At the end of the operation, the system provided an array of force, the moment of joints and estimated GRF data. This technique was applied to all resistive exercises.

Subsequently, to evaluate optimal load level for each type of resistive exercise, a cost function which is given formula (6) was calculated as a function of load in microgravity state.

$$J(L) = \frac{1}{2M}\sum_{i=1}^{M}(\hat{y}_i - y_i)^2 \tag{6}$$

where M is the total number of frames, $\hat{y}_i$ is the value of moment given the load L which changes by time instant i in microgravity conditions, y_i is the value of moment given in constant load (L=54 kg) in actual gravity state (g=9.81m/s^2). The cost function was calculated for statistic purposes thus it represents a mean square error between moments of each joint under different gravity conditions as a function of load. In addition, optimal load level was tried to figure out to evaluate a reference load for strengthing the muscles on the lower extremity in microgravity condition with different resistive exercises.

3. RESULTS

Throughout the several training, a total of 5 reps for each resistive exercise sessions were performed with no adverse events related to the device or to the study. Results are presented as mean of graphical representation for each moment of joints and a cost function to find an optimal load level for achieving maximum strength level in muscles with respect to all joint moments in the exercise program. Each graph represents one completed exercise cycle. The moment quantities were normalized by the division of BW. In the following moment graphs, the impact of microgravity condition and change in load on joint moment were shown. The same procedure was employed to visualize the data corresponding to the four resistive exercises.

3.1. Regular Squat

In figure 3.1, figure 3.2 and figure 3.3, the moment of the ankle, knee, and hip joints were shown. The blue thick line in the graph represents the moment of force in normal gravity condition under constant load L=54 kg. The lines from blue to light green indicates the moment as a function of varying load levels. Similar shape, trend, and sign between the knee and hip moments but different behavior at the ankle moment was monitored owing to their flexion and dorsiflexion state respectively in the squat. In the figures, 3.2 and 3.3 converging behavior was shown. On the hand, when using heavier weight in microgravity state, a larger sagittal moment on the hip and knee joint, but a lower sagittal moment on the ankle joint was observed. Here, the increasing or decreasing of moments of joint depends on sign convention which means positive moment occurs in the counterclockwise or vice versa. Moreover, in the end, frames of ankle moment, a sharp decline due to artifacts in the trajectory sequences was observed.

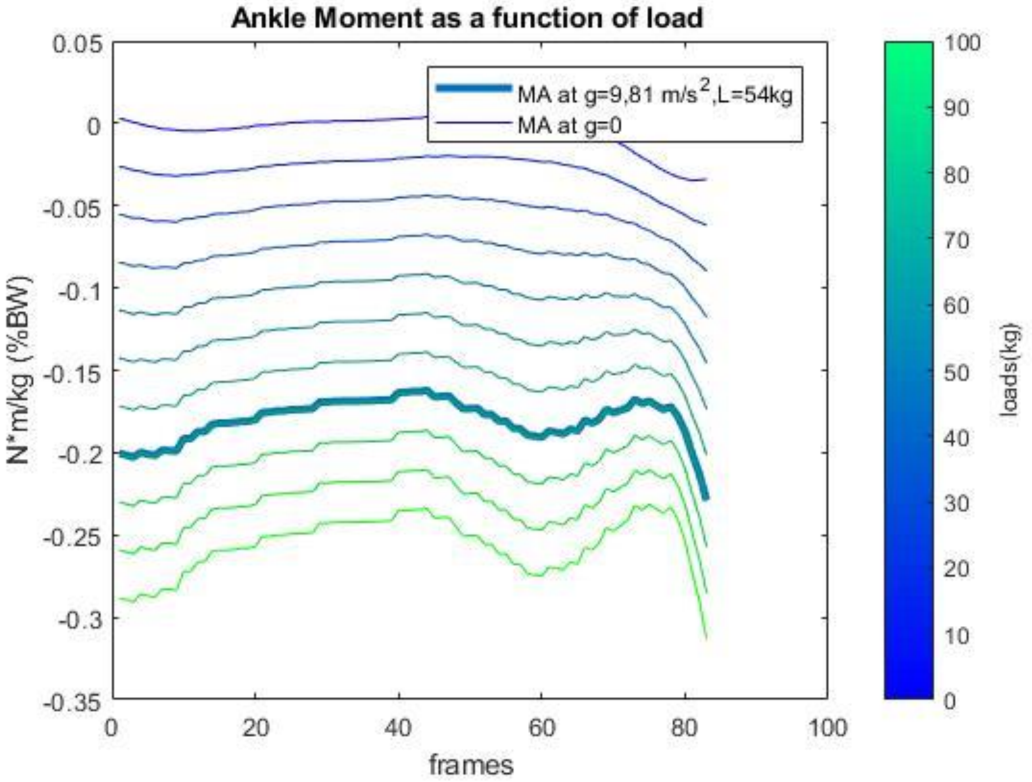


Figure 3. 1 Moment of ankle joint under different load levels

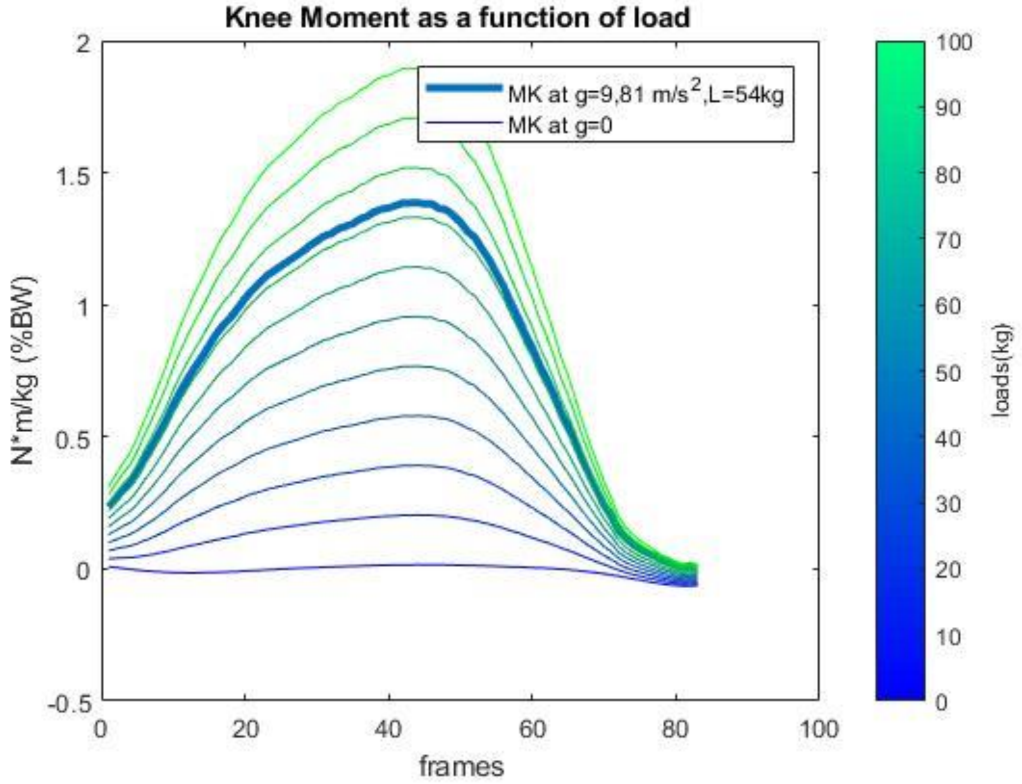


Figure 3. 2 Moment of knee joint under different load levels

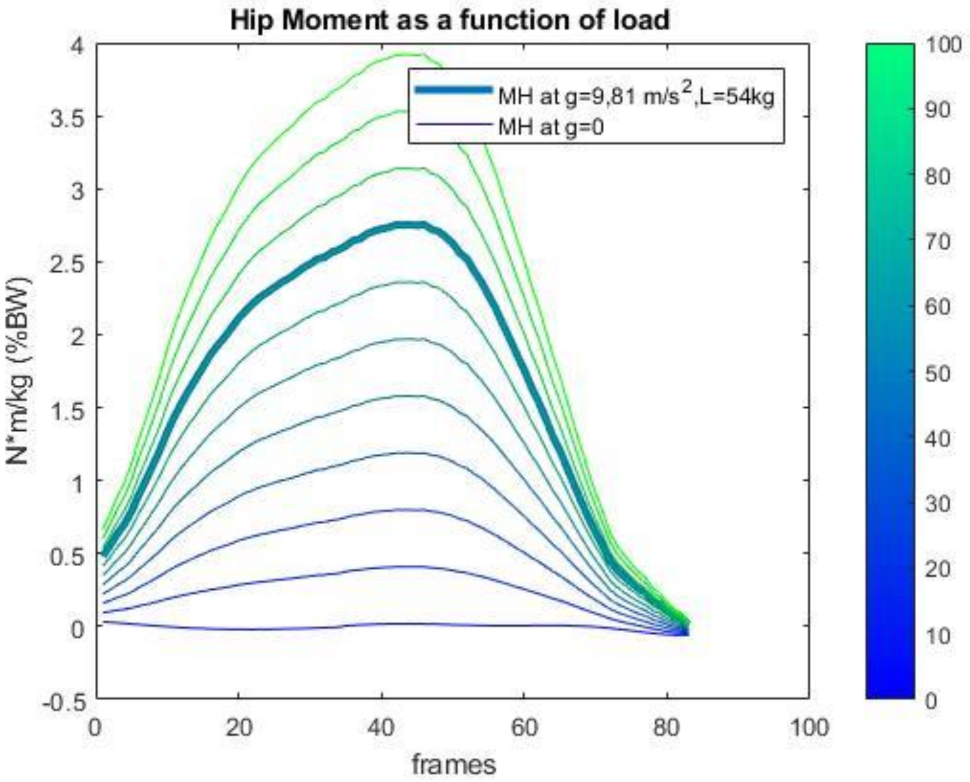


Figure 3. 3 Moment of the hip joint under different load levels

In figure 3.4, cost function with particularly examined load range in the regular squat was shown. The intersected load level of each joint moment was indicated in figure 3.4.

For a whole range of load levels, 70 kg was suggested but when going into the specific range of load, the optimal load was evaluated as ~71 kg.

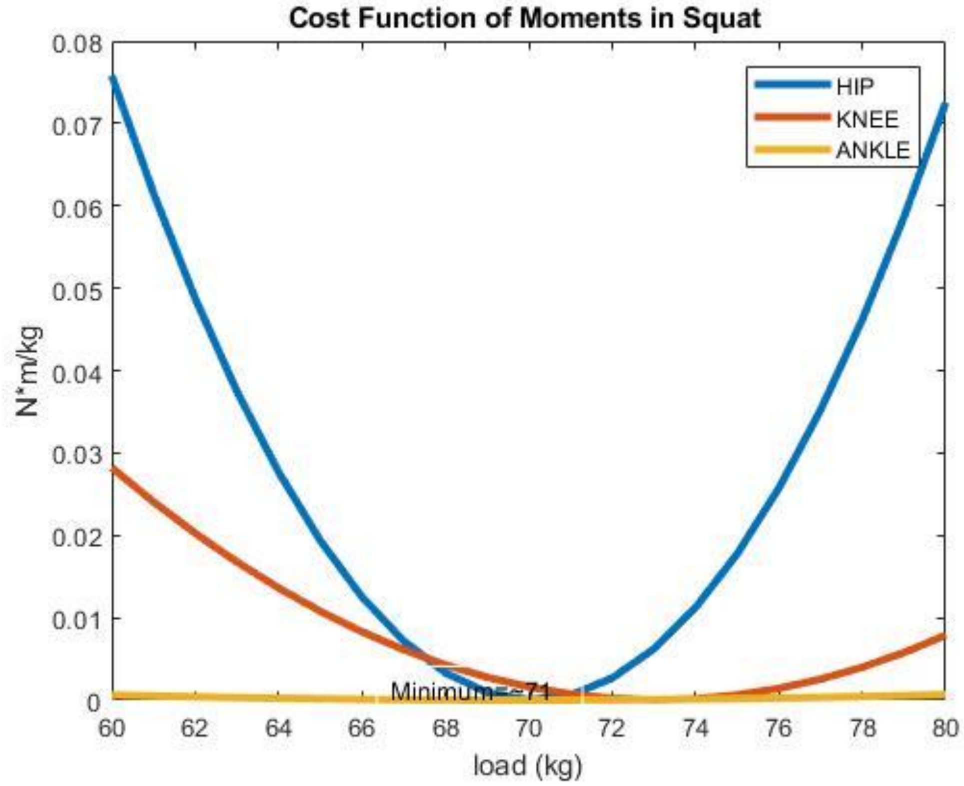


Figure 3. 4 The cost function which shows the optimal load in a specific range in regular squat

3.2. Wide Leg Squat

In figure 3.5, figure 3.6 and figure 3.7 the moment of the ankle, knee, and hip joint in wide leg squat was demonstrated below. The blue thick line in the graph represents the moment of force in normal gravity condition under fixed load L=54 kg. The lines from blue to light green represents the moment as a function of varying load levels. The tendency of graphs of joint moments had similar behavior with the regular squat.

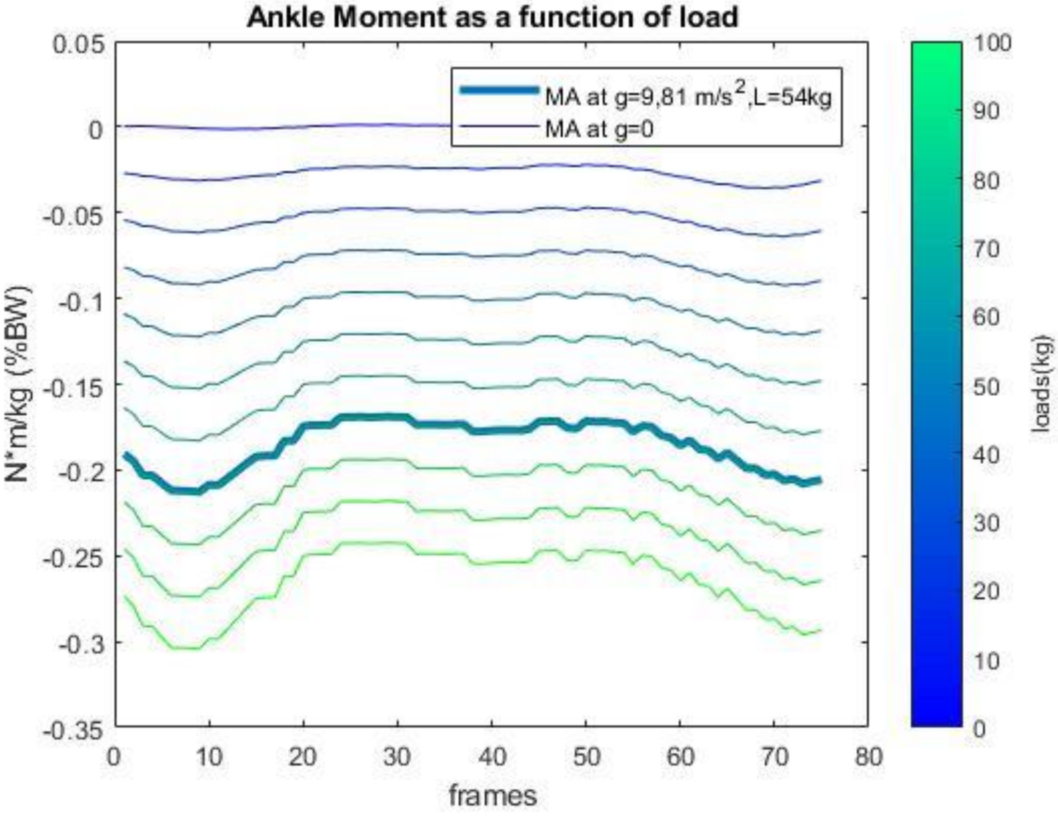


Figure 3. 5 Moment of ankle joint under different load levels

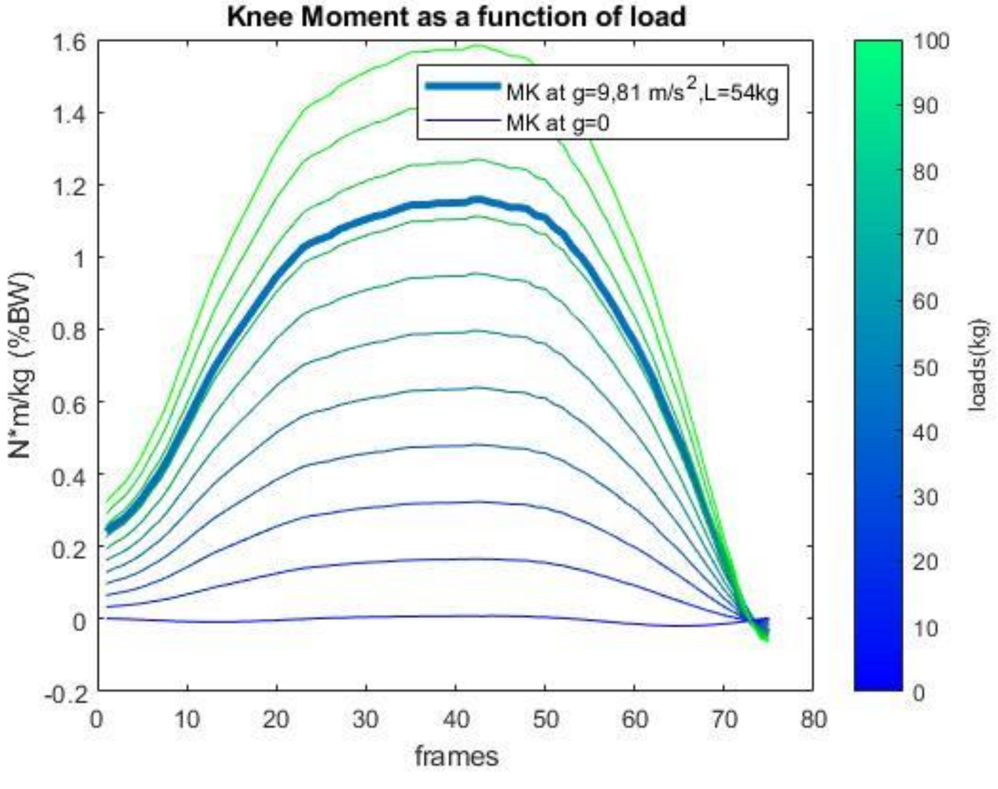


Figure 3. 6 Moment of the knee joint in a wide squat under different load levels

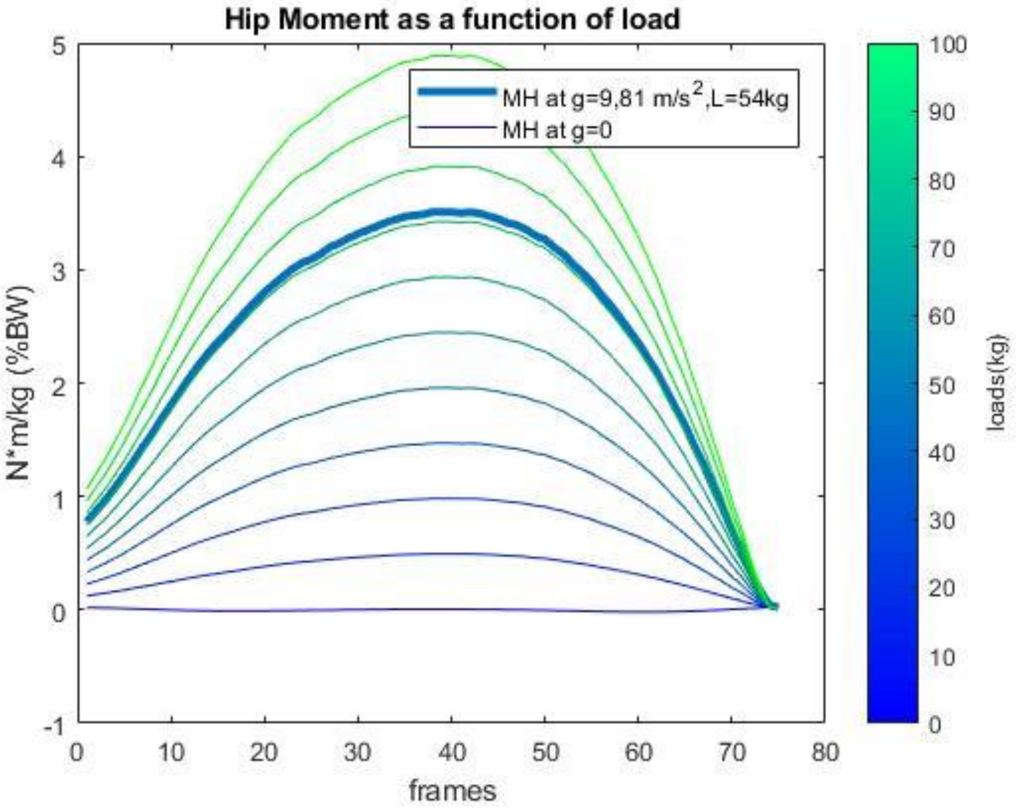


Figure 3. 7 Moment of hip joint for wide squat under different load levels

In the following graph, the cost function based on hip, knee and ankle joint moment was shown. In figure 3.8, the cost function in the zoomed range between 60-80 kg was analyzed.

Although the suggested load was 70 kg in whole load range, the suggested load level became 72 kg as shown in figure 3.8.

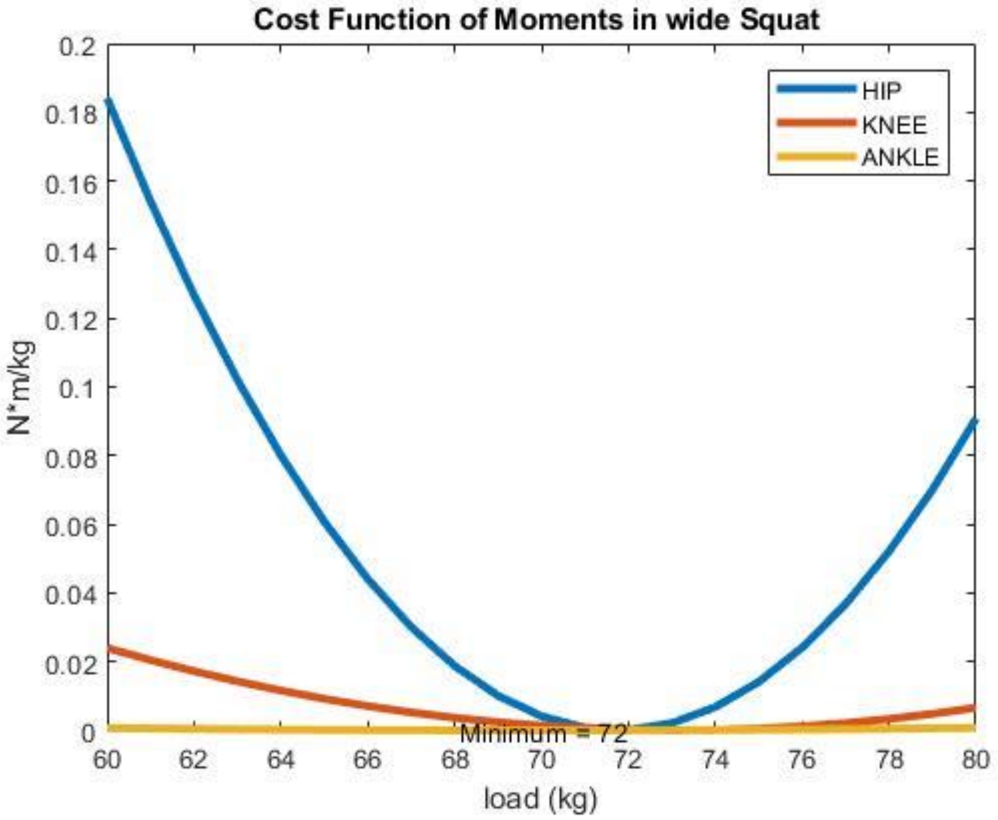


Figure 3. 8 The cost function which shows the optimal load in specific load range in wide leg squat

3.3. Deadlift

The moment of ankle, knee, and hip joint in the deadlift were shown in figure 3.9, figure 3.10 and figure 3.11. The blue thick line in the graph represents the moment of force in normal gravity condition under fixed load L=54 kg. The lines from blue to light green represents the moment as a function of varying load levels. A sharp drop between the frames 40 – 50 was observed in all joint moment graphs due to artifacts occurred when processing data.

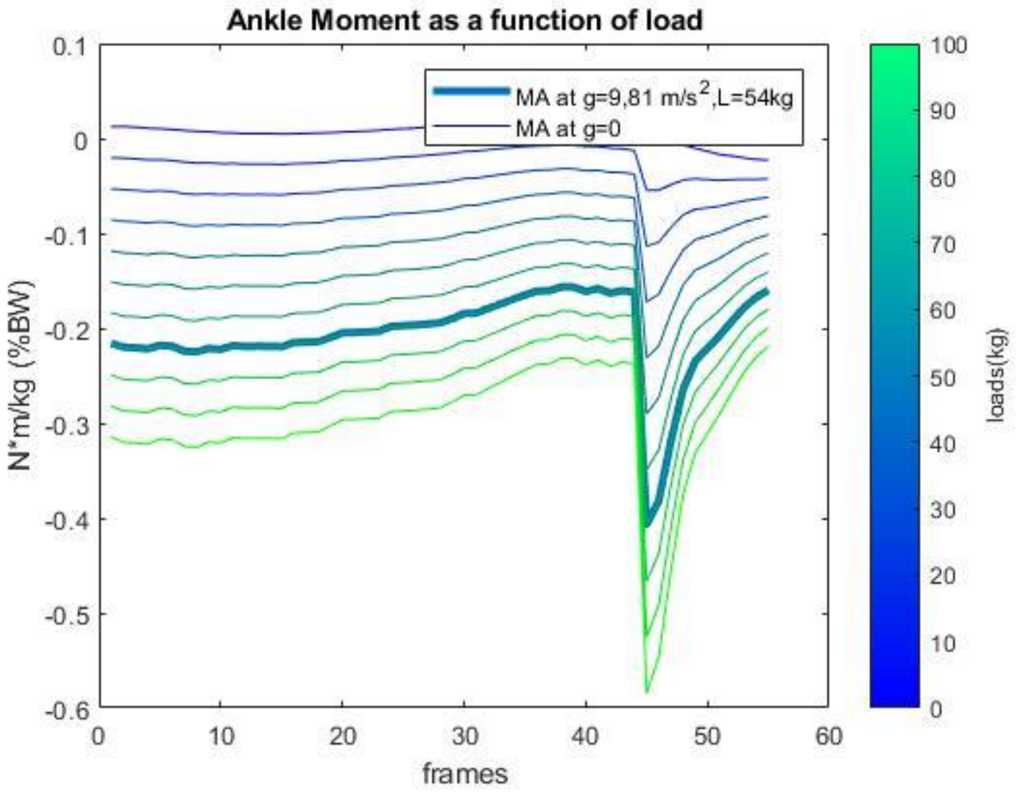


Figure 3. 9 Moment of the ankle joint in deadlift under different load levels

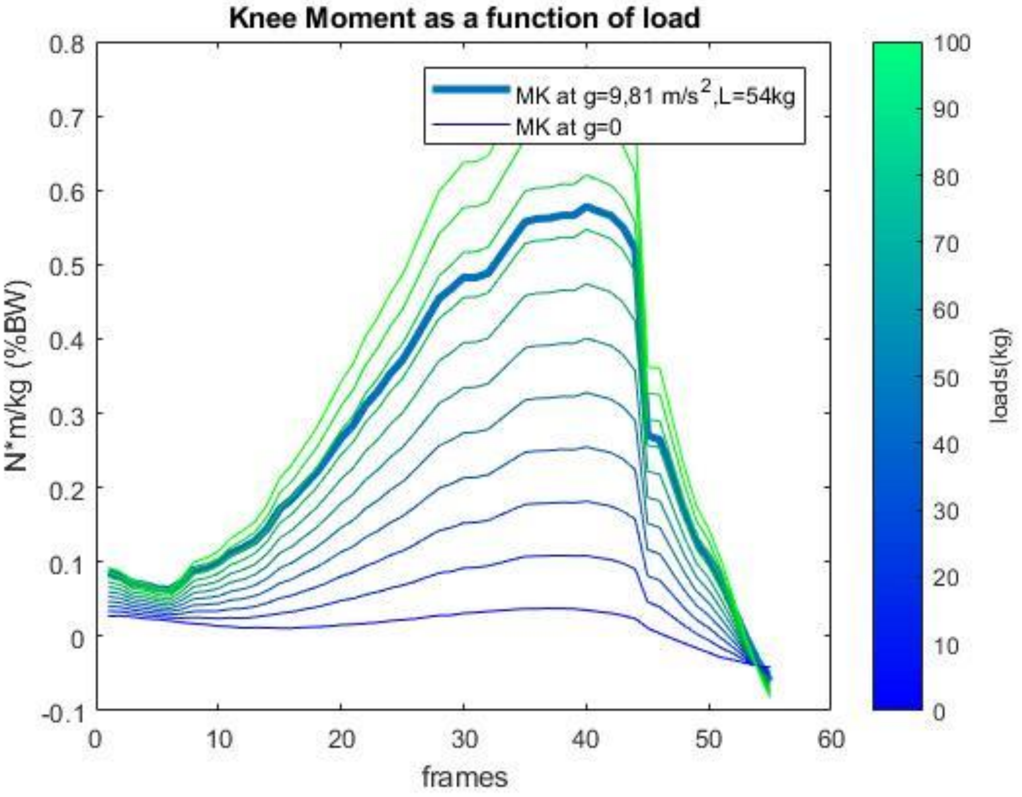


Figure 3. 10 Moment of the knee joint in deadlift under different load levels

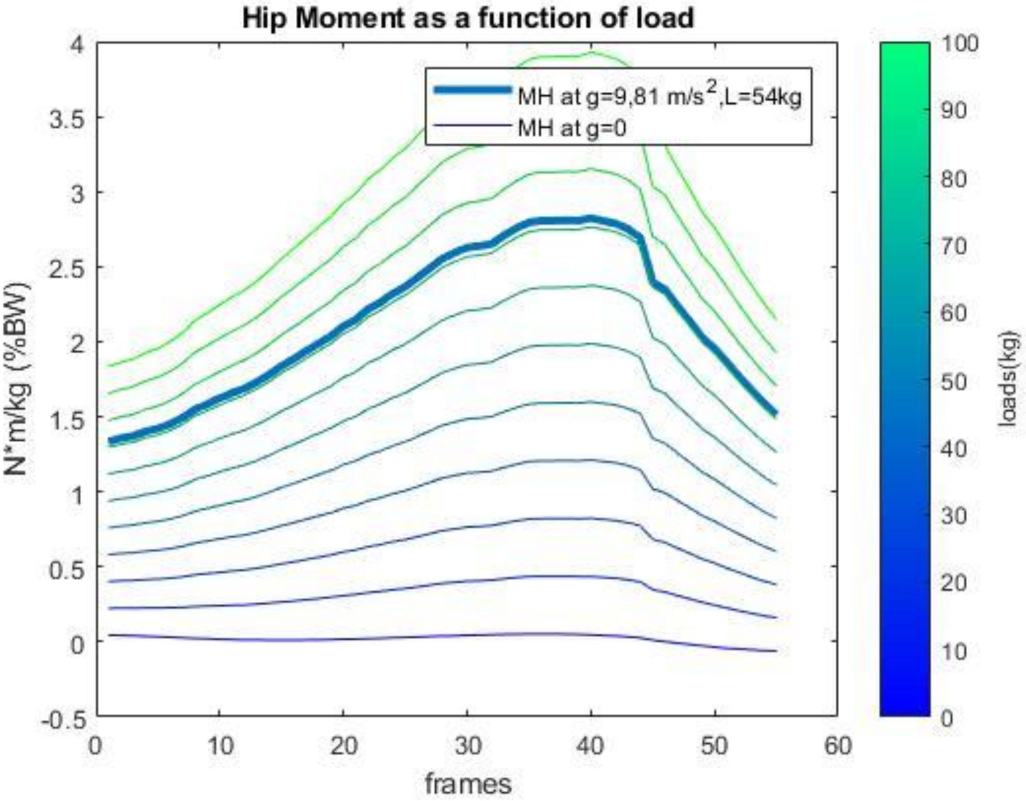


Figure 3. 11 Moment of the hip joint in deadlift under different load levels

In the following figure, the cost function which was calculated from hip, knee and ankle joint moment was shown. In the figure 3.12, the cost function in the specific load range between 60-80 kg was investigated.

Based on whole load range analysis, the suggested load level was 70 kg, however, when investigating the specific load range from 60 to 80 kg, it was obviously seen that suggested load level is shown as 71 kg.

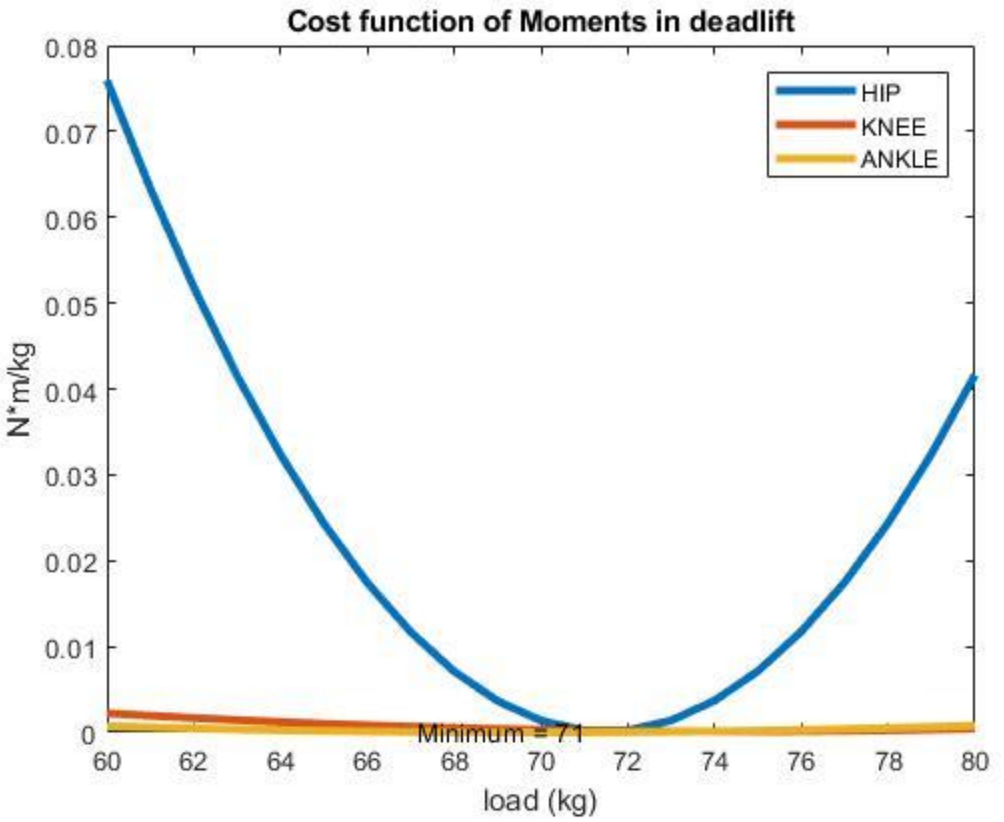


Figure 3. 12 A cost function is represented in a specific range of load in the deadlift

3.4. Single Leg Squat

In the figure 3.13, figure 3.14 and figure 3.15, the moment of the ankle, knee, and hip joint in single leg squat was represented. The blue thick line in the graph represents the moment of force in normal gravity condition under fixed load L=54kg. The lines from blue to light green represents the moment as a function of varying load levels. The movement behavior was obviously seen that in the figure 3.13 and figure 3.14. However, the hip joint moment has a similar increasing and decreasing shape with other resistive exercises.

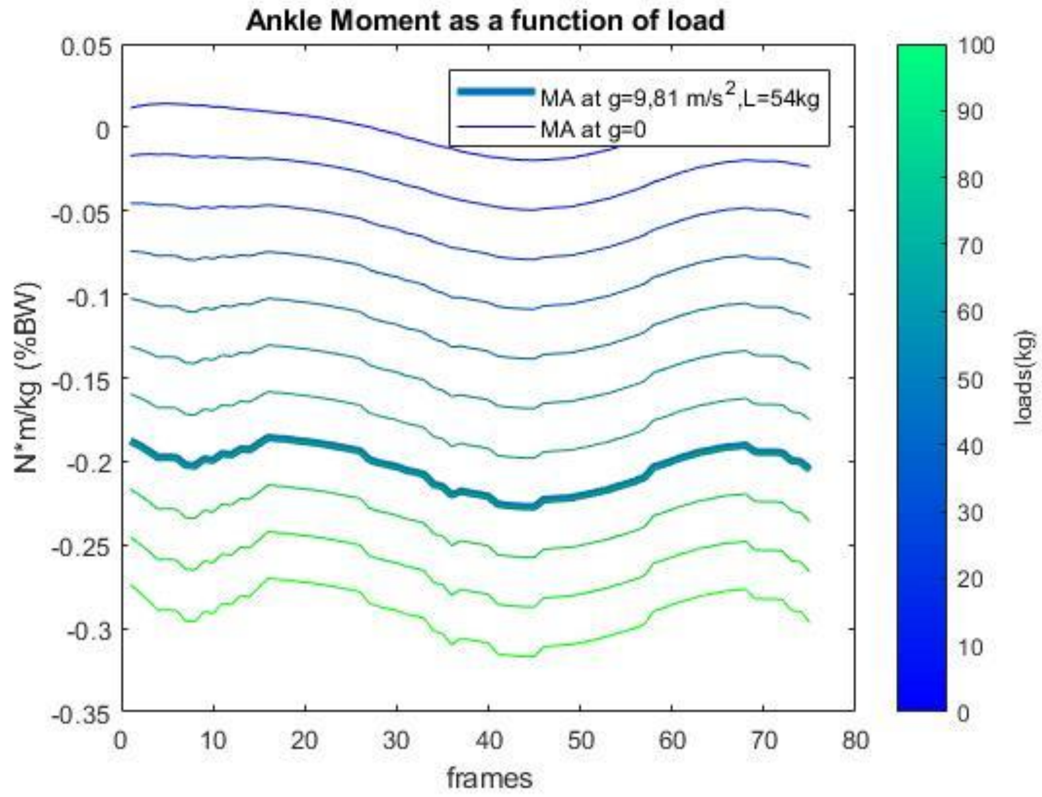


Figure 3. 13 Moment of the ankle joint in single leg Squat under different load levels

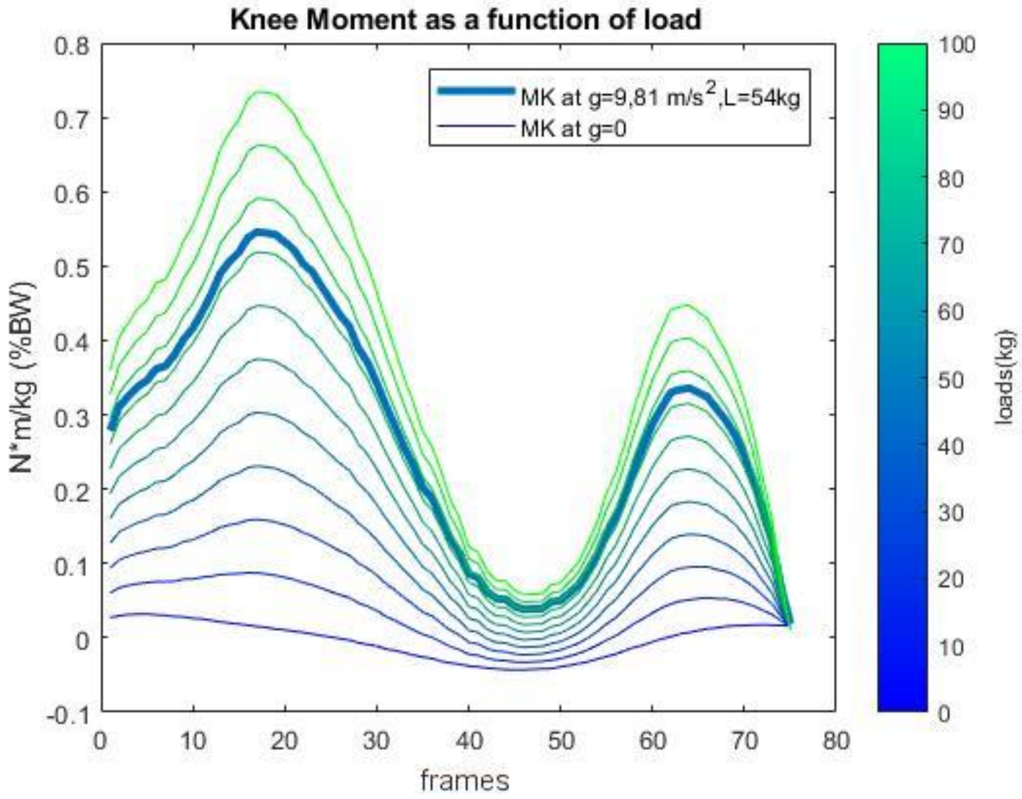


Figure 3. 14 Moment of the knee joint in single leg Squat under different load levels

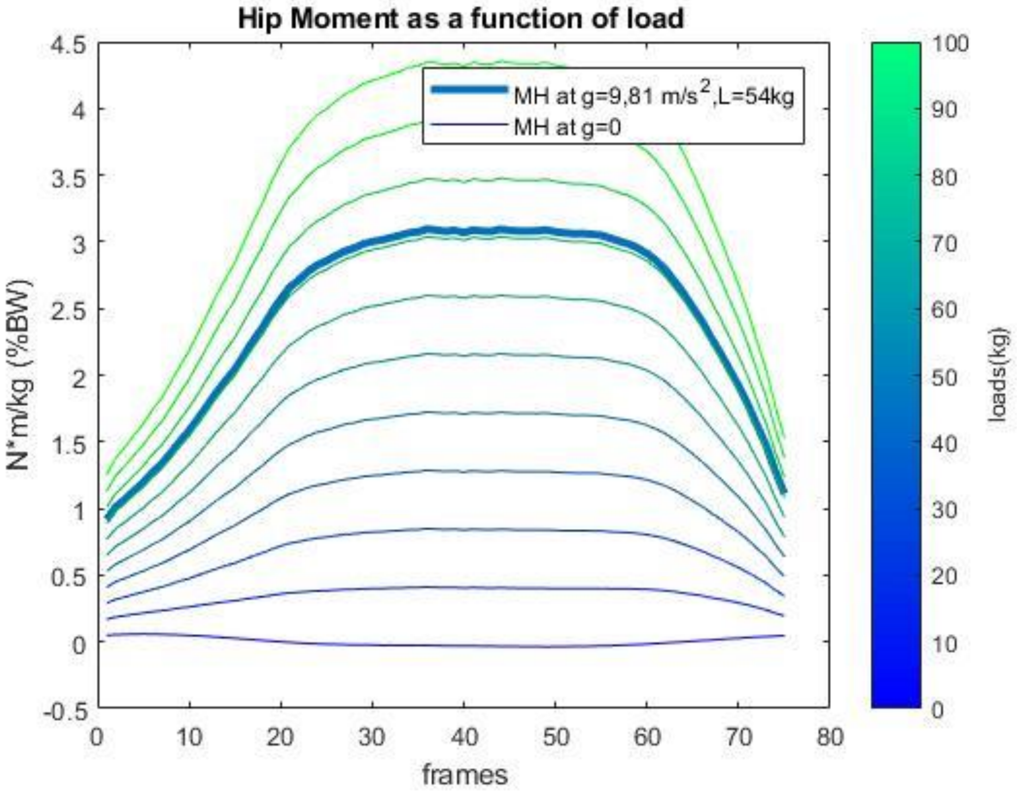


Figure 3. 15 Moment of the hip joint in single leg Squat under different load levels

In the graph below, the cost function based on hip, knee and ankle joint moment was shown. In figure 3.16 the cost function in the conservative choice of load range between 60-80 kg was analyzed.

While the suggested load level was 70 kg, however, the suggested load level was evaluated as 71 kg as shown in figure 3.16.

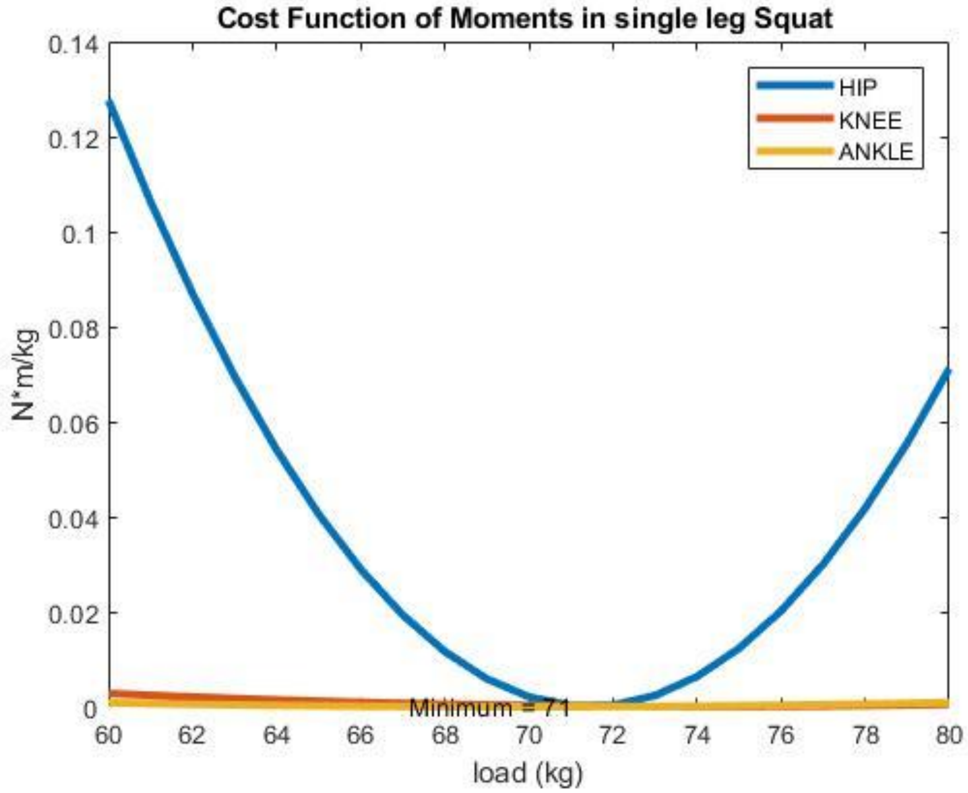


Figure 3. 16 The cost function which shows the optimal load in specific load range in single leg squat

4. DISCUSSION

In this section, the discussion will point to suggestions, evaluations, limitations of work and assumptions that provide a complete data set. Besides, all conservative choices will be explained clearly.

The four exercises exhibited for the lower extremities, but not for the trunk. The study was employed by Petersen et al. expressed that during prolonged exposure to microgravity, to maintain the effect of load in resistive exercises, absolute training load should be increased rather than decreased or assumed same [40]. Also, another study conducted by Dewitt et al. suggested that the compensation for the absence of body weight, 70% of their body weight to the bar load should be added for the crewmembers' exercise in microgravity [41]. Therefore moment measurements were obtained as a function of load starting from 0 to 100 kg in a way that includes the constant exercise load 54 kg. To evaluate particular load range, the moment of lower extremity joints were analyzed in the range between 60-80 kg. The graphs of regular squat have shown that by increasing load level, at the knee and hip joint a higher moment can be achieved. Therefore, increasing moment on the joint level leads to high-level fitness for the muscles and overall health. In contrast, at the ankle joint, by increasing load level, the lower moment was observed. Due to the limited number of studies about squat and squat like resistive exercises either on Earth gravity or in microgravity conditions, there were no several opportunities to check the results with related researches. However, according to some studies, the results were convenient according to figure 4.1 [42][45][46]. The impact of increasing the load on the joints is obviously different due to sign convention (flexion of knee and hip is positive, but dorsiflexion of the ankle joint is negative). To find the optimal load, the cost function which is briefly described in data processing part was used. The thick line on each moment graph represents the moment under normal gravity and constant load, L=54 kg. The lines degraded from blue to light green describes how load affects the moment under microgravity condition, g=0. As figure 3.4 suggested that optimal load level for regular squat under microgravity to mimic earth gravity condition, was 71 kg.

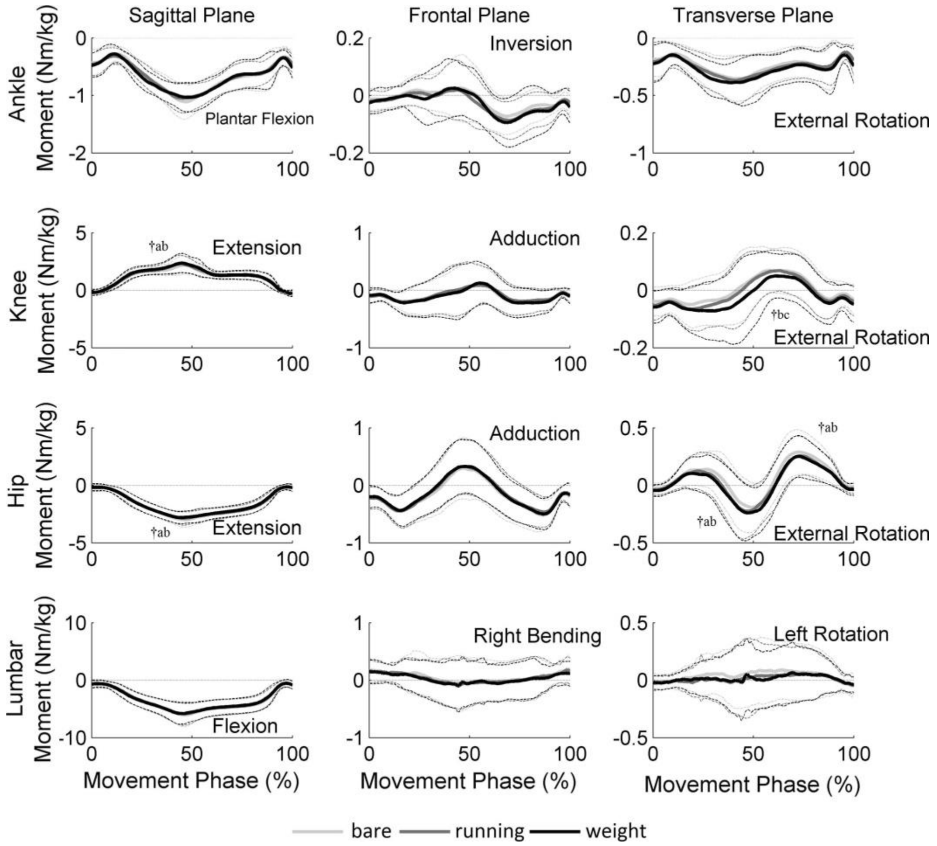


Figure 4. 1 The moment of Ankle, knee, and hip was shown based on different modalities bare (light gray), running(gray) and squat with weight (black) [42]

In wide leg squat, the same moment trend was observed. On the basis ofthe figure 4.8 currently available, it was obvious to suggest that optimal load level for wide leg squat is 72 kg to have the same effect on the muscles in the microgravity state.

In the deadlift, same moment trend based on a change in load was observed with some artifacts between the frames 40 -50. Therefore, the change in moment value with respect to frames was different than regular and wide leg squat. The only joint affected greatly by the magnitude of the load was the knee. As the load increased from 0 to 100, the amount of internal flexion during the final phase of the deadlift decreased. The cost function at the specific range of load starting from 60 to 80 kg of each joint moment propounded that optimal load is 71 kg to reach a suggested impact on muscles.

In single leg squat, different moment sequences based on a change in the load levels were observed especially in knee joint moment. However, it is easily seen gradual movement. While the change in moment value with respect to frames are different than regular and wide leg squat for knee and ankle joint moment, change in a moment of hip joint was similar. A different shape of knee moment might be occurred by increasing variation of acceleration. As indicated in the literature, even only one segment can be affected in a squared way when the variation of acceleration increases rapidly because the moment of inertia will differ with the distribution of mass about the same axis depends on velocity [43]. Subsequently, the cost function at the specific range of load starting between 60-80 kg of each joint moment propounded that optimal load is 71 kg to reach efficient results on muscles.

The error in some results might be occurred because of simulated microgravity state. In 0G, the body weight is 0, so all load must be applied by a bar on the shoulder while doing squat. As indicated in the study employed by Fregly et al. the accuracy of moment prediction between simulated microgravity and on the ISS should be within about 6% RMS error to give confident results but most of the times, this percentage is higher because of weight distribution in the human body [45]. The load is experienced starting from top to bottom, so exposure to load at the knee level will be reduced compared to the hip joint.

The obtained moments in this study was compared with the figure 4.2, shows the moment of joint with experimental loads on Earth versus simulated loads on Earth.

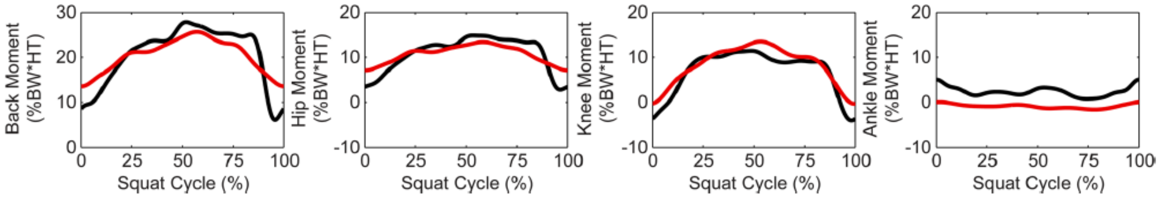


Figure 4. 2 The moment of joints with experimental loads on Earth in black versus ISS simulated loads on Earth in red [45]

The other contributions to uncertainties and errors might be caused by estimation of body segment parameters due to their effect and sensitivity over the net joint moment [46].

4.1. Limitations and Assumptions

The study was limited by following issues;

1. Load on the hip joint
2. Working under 2D conditions
3. Technical issues
4. Number of subjects

In this experiment, the strongest and important limitation was the load on the hip joint instead of being on shoulders. Since the squat was done with the resistive bar acting like a load on the shoulders. Thus, in theory, primary load impact and contact with the body should have been with shoulders. Nevertheless, due to neither having marker trajectories of shoulder nor lack of marker trajectory of the scapula, the upper extremity data were unknown or unreliable to compute force and moment quantities in the upper extremity. Therefore, the load was assumed that it has direct contact with hip joint pointed rigidly downward so calculations were conducted up to hip joint level.

Secondly, all calculations were evaluated under two-dimensional kinematics principle based on the sagittal plane due to having a simpler evaluation pathway. The fact that, 3D kinematic evaluations, requires heavily on vector operations and matrix algebra for linear and rotational transformations between coordinate systems, calculation of angular parameters, etc.

Third, the data acquired from a motion capture system were not fully completed (due to markers not recorded by the cameras for a certain amount of time), although it was tracked in a meticulous way. Thus the estimation of some marker trajectories such as the trajectory of the scapula was almost unfeasible to use in calculations. For this reason, trunk moment could not be operated.

The final limitation was a number of subjects. In this experiment, there was a single male subject thus there were no other data or control group to compare resultant moment functions of each joint in the lower extremity. The only comparisons were considered with literature studies which are based on topics resistive exercise and improving muscle strength.

Furthermore, the following assumptions were considered while in the processing stage. The first assumption was about CoP. Due to widespread of pressure points (points are even out of force plates) in the capturing range, experimental CoP was not extracted so the theoretically estimated CoP was calculated based on coefficients of anthropometry. In addition, CoP was assigned as an average point on x-axis between the center of mass of foot and ankle joint, on y-axes on the origin of the global reference frame.

The second assumption was about reaction forces on the hip joint (great trochanter). On the x-axis and y-axis, the reaction force of hip joint was assumed as null because the trunk was not taken into account for moment calculations and there is no contact point between Trochanter and Pelvis. The force of hip joint in the vertical direction has mainly consisted of load and gravitational effect on summed segment mass such as head, arm, trunk, and thigh. In the summed mass, only bi-lateral side of the body was considered.

5. CONCLUSION

Both short and long duration space flight results in decrements of muscle fitness. Decrements include muscle atrophy, reduced strength, reduced power and lowering of fatigue resistance. The effects are primarily observed in the lower limbs and other postural muscles. To prevent and recover the impact of microgravity on the muscles, resistive exercises such as the squat with different configurations and several load levels needed to be explored. To apply those resistive exercises properly, the ARED machine was created by NASA.

The ARED allows to perform different resistive exercises with different load levels generated by specific vacuum cylinders and flywheel belongs to the device. The exercises including shoulder presses, bench presses with bar, and other seated or lying can be performed within the machine. In microgravity state, astronauts could not feel the gravity effect so the absence of gravity on the body and exercise equipment hinders the muscle building properly. The facility of ARED is providing actual load even in the microgravity state. However, the challenging issue here is to find a required load level either to preserve or recover the body fitness. At this point, this study was significant to find an optimal load level for maintaining the muscle strength. Required load levels were obtained based on the influence of resistive exercises on the body.

Literature relative to the biomechanics of the dynamic squat and exercises such as regular squat, wide leg squat, single leg squat and deadlift that are resulting similar impacts on the body were considered. The effect of dynamic squat under normal and microgravity condition with varying loads was the focus of this study.

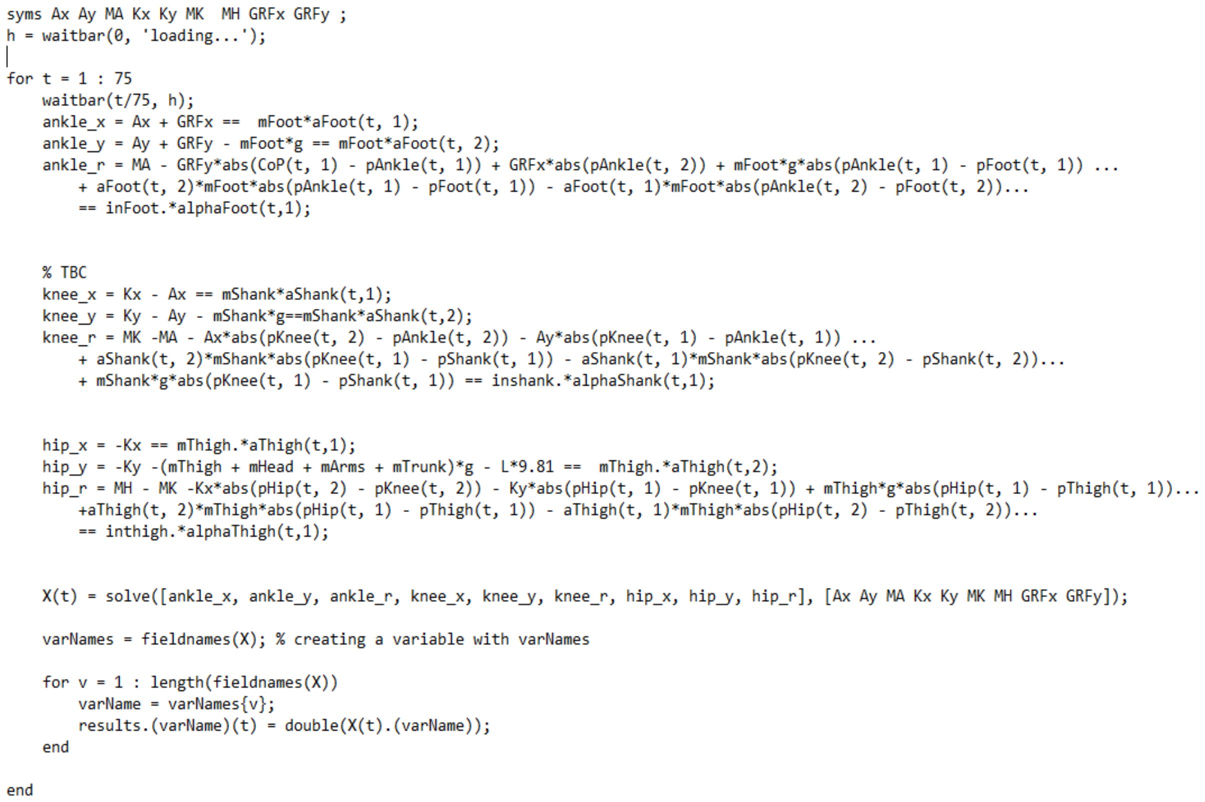
At the beginning of the study, literature was reviewed as shown in discussion part. With respect to results of some studies [40], obtained values both force and moment of joints was computed and to be more precise, different calculation platforms were used. Instantaneously, in Excel, a traditional Newton-Euler inverse dynamics method was proposed to find the net joint moment at the ankle, knee, and hip throughout the resistive exercise cycles with respect to Earth's gravity state. After some results and graphs were obtained in Excel, the calculations were repeated in Matlab with System of equations method. Outputs of the method were force and moment of each joint to compute the cost function. The computation of cost function of each moment of force and evaluating three cost function based on the ankle, knee, and hip respectively in the same load range, provided unique load level for every resistive exercise. The results have provided some evidence that current resistive exercises for crew members may be sufficient for every joint in lower extremity if resulting load is used.

In conclusion, the results are limited to our single-subject study and considering all the limitations stated, we could hypothesize that a proper load can be 85% of BW in microgravity state.

APPENDIX

In the following, a sample of the Matlab code used to set the system of Newton's equations was provided. At first, we defined the symbolic variables the system will be solved for. In the second part, the system of nine equation was defined. In the third, we used the command below to get the numerical values of each unknown variable. This process was repeated at each time frame.

X(t)=solve([ankle_x, ankle_y, ankle_r, knee_x, knee_y, knee_r, hip_x, hip_y, hip_r], [A_x A_y *MA* K_x K_y *MK MH* GRF_x GRF_y*]);*



```
syms Ax Ay MA Kx Ky MK  MH GRFx GRFy ;
h = waitbar(0, 'loading...');

for t = 1 : 75
    waitbar(t/75, h);
    ankle_x = Ax + GRFx ==  mFoot*aFoot(t, 1);
    ankle_y = Ay + GRFy - mFoot*g == mFoot*aFoot(t, 2);
    ankle_r = MA - GRFy*abs(CoP(t, 1) - pAnkle(t, 1)) + GRFx*abs(pAnkle(t, 2)) + mFoot*g*abs(pAnkle(t, 1) - pFoot(t, 1)) ...
        + aFoot(t, 2)*mFoot*abs(pAnkle(t, 1) - pFoot(t, 1)) - aFoot(t, 1)*mFoot*abs(pAnkle(t, 2) - pFoot(t, 2))...
        == inFoot.*alphaFoot(t,1);


    % TBC
    knee_x = Kx - Ax == mShank*aShank(t,1);
    knee_y = Ky - Ay - mShank*g==mShank*aShank(t,2);
    knee_r = MK -MA - Ax*abs(pKnee(t, 2) - pAnkle(t, 2)) - Ay*abs(pKnee(t, 1) - pAnkle(t, 1)) ...
        + aShank(t, 2)*mShank*abs(pKnee(t, 1) - pShank(t, 1)) - aShank(t, 1)*mShank*abs(pKnee(t, 2) - pShank(t, 2))...
        + mShank*g*abs(pKnee(t, 1) - pShank(t, 1)) == inshank.*alphaShank(t,1);


    hip_x = -Kx == mThigh.*aThigh(t,1);
    hip_y = -Ky -(mThigh + mHead + mArms + mTrunk)*g - L*9.81 ==  mThigh.*aThigh(t,2);
    hip_r = MH - MK -Kx*abs(pHip(t, 2) - pKnee(t, 2)) - Ky*abs(pHip(t, 1) - pKnee(t, 1)) + mThigh*g*abs(pHip(t, 1) - pThigh(t, 1))...
        +aThigh(t, 2)*mThigh*abs(pHip(t, 1) - pThigh(t, 1)) - aThigh(t, 1)*mThigh*abs(pHip(t, 2) - pThigh(t, 2))...
        == inthigh.*alphaThigh(t,1);


    X(t) = solve([ankle_x, ankle_y, ankle_r, knee_x, knee_y, knee_r, hip_x, hip_y, hip_r], [Ax Ay MA Kx Ky MK MH GRFx GRFy]);

    varNames = fieldnames(X); % creating a variable with varNames

    for v = 1 : length(fieldnames(X))
        varName = varNames{v};
        results.(varName)(t) = double(X(t).(varName));
    end

end
```

REFERENCES

[1] Aeronautics and Space Engineering Board, National Research Council, Advanced Technology for Human Support in Space (Washington, DC: National Academy Press, 1997).

[2] Center, Johnson Space. "Advanced Resistive Exercise Device (ARED) Man-In-The-Loop Test (MILT)." (2006).

[3] Moretti, Marlene M, and Maya Peled. “Adolescent-Parent Attachment: Bonds That Support Healthy Development.” Paediatrics & Child Health 9.8 (2004): 551–555. Print.

[4] Gilles Clément, Angeli Bukley. ‘“Artificial Gravity", Springer Science& Business Media, 2007, 1552–1566.

[5] Adams, G.R., Hather, B.M., Dudley, G.A. Effect of short-term unweighting on human skeletal muscle strength and size. Aviation Space and Environment Medicine. 1994;65:1116–1121.

[6] Berg, H.E., Tesch, P.A. Changes in muscle function in response to 10 days of lower limb unloading in humans. Acta Physiologica Scandinavica. 1996;157:63–79.

[7] Baldwin, K.M. Effects of altered loading states on muscle plasticity (what have we learned from rodents?). Medical Science and Sports Exercise. 1996;28

[8] Hargens, Alan R., Roshmi Bhattacharya, and Suzanne M. Schneider. "Space physiology VI: exercise, artificial gravity, and countermeasure development for prolonged space flight." European journal of applied physiology 113.9 (2013): 2183-2192.

[9] Baroni, G., Ferrigno, G., Anolli, A., Andreoni, G., and Pedotti, A. (1998). Quantitave analysis of motion control in microgravity. Acta Astronautica, 43(6);131-151

[10] Fitts, R.H., Riley, D.R., Widrick, J.J. Functional and structural adaptations of skeletal muscle to microgravity. The Journal of Experimental Biology. 2001;204:3201–3208

[11] Brown, SP (2000). Introduction to exercise science. Lippincott Wims & Wilkins. pp. 280–1. ISBN 0-683-30280-9.

[12] Kritz, Matthew, John Cronin, and Patria Hume. "The bodyweight squat: A movement screen for the squat pattern." Strength & Conditioning Journal 31.1 (2009): 76-85.

[13] Escamilla, RF, Fleisig, GS, Zheng, N, Lander, JE, Barrentine, SW, Andrews, JR, Bergemann, BW, and Moorman, CT. Effects of technique variations on knee biomechanics during the squat and leg press. Med Sci Sports Exerc 33: 1552–1566, 2001a.

[14] Fry, AC, Smith, JC, and Schilling, BK. Effect of knee position on hip and knee torques during the barbell squat. J Strength Cond Res 17: 629–633, 2003.

[15] Nisell, R and Ekholm, J. Joint load during the parallel squat in powerlifting and force analysis of in vivo bilateral quadriceps tendon rupture. Scand J Sports Sci 8: 63–70, 1986.

[16] Solomonow, M, Baratta, R, Zhou, BH, Shoji, H, Bose, W, Beck, C, and D’Ambrosia, R. The synergistic action of the anterior cruciate ligament and thigh muscles in maintaining joint stability. Am J Sports Med 15: 207–213, 1987

[17] McCurdy K, O’Kelley E, Kutz M, Langford G, Ernest J, and Torres M. Comparison of lower extremity EMG between the 2-leg squat and modified single-leg squat in female athletes. J Sport Rehabil 19: 57–70, 2010.

[18] Crossley KM, Zhang W, Schache AG, Bryant A, and Cowan SM. Performance on the single-leg squat task indicates hip abductor muscle function. Am J Sport Med 39: 866–873, 2011

[19] Willy RW Davis IS. The effect of a hip-strengthening program on mechanics during running and during a single-leg squat. J Orthop Sports Phys Ther. 2011;41(9):625-632. Int J Sports Phys Ther. 2016 Apr; 11(2): 201–211.

[20] Escamilla, Rafael F., et al. A three-dimensional biomechanical analysis of sumo and conventional style deadlifts. Medicine and science in sports and exercise 32.7 (2000): 1265-1275.

[21] Cormie, P, McCaulley, GO, Triplett, TN, and McBride, JM. Optimal loading for maximal power output during lower-body resistance exercises. Med Sci Sports Exerc 39: 340-349, 2007.

[22] Brown, EW, and Abani, K. Kinematic and kinetics of the dead lift in adolescent power lifters. Med Sci Sports Exercise 17: 554-566, 1985

[23] Signorile, JF, Kwiatkowksi, K, Caruso, JF, and Robertson, B. Effect of foot position on the electromyographical activity of the superficial quadriceps muscles during the parallel squat and knee extension. J Strength Cond Res 9: 182–187, 1995.

[24] Escamilla, RF. Knee biomechanics of the dynamic squat exercise. Med Sci Sports Exerc 33: 127–141, 2001.

[25] Li, G, Most, E, DeFrate, LE, Suggs, JF, Gill, TJ, and Rubash, HE. Effect of the posterior cruciate ligament on posterior stability of the knee in high flexion. J Biomech 37: 779–783, 2004a.

[26] Kritz, Matthew, John Cronin, and Patria Hume. "The bodyweight squat: A movement screen for the squat pattern." Strength & Conditioning Journal 31.1 (2009): 76-85.

[27] Hung, YJ and Gross, MT. Effect of foot position on electromyographic activity of the vastus medialis oblique and vastus lateralis during lower-extremity weight-bearing activities. J Orthop Sports Phys Ther 29: 93–102, 1999.

[28] White, Gannon A. Running tactics and segmental coordination on various levels of incline. University of Northern Colorado, 2011.

[29] Glassbrook, Daniel J., et al., A Review of the Biomechanical Differences Between the High-bar and Low-bar Back-squat, The Journal of Strength & Conditioning Research 31.9 (2017): 2618-2634.

[30] Donnelly, DV, Berg, WP, and Fiske, DM. The effect of the direction of gaze on the kinematics of the squat exercise. J Strength Cond Res 20: 145–150, 2006.

[31] Russell C. Hibbeler (2009). "Kinematics and kinetics of a particle". Engineering Mechanics: Dynamics (12th ed.). Prentice Hall. p. 298.

[32] Martin, George, Kinematics and Dynamics of Machines, 2nd ed., Waveland Press Inc., Long Groove, IL, 2002

[33] T.W. Lu, S.J. Taylor, J.J. O’Connor, P.S. Walker Influence of muscle activity on the forces in the femur: an in vivo study J Biomech, 30 (1997), pp. 1101-1106

[34] Winter, D.A. 1990. Biomechanics and Motor Control of Human Movement. 2nd ed. Toronto: John Wiley & Sons, p. 104-119

[35] Zatsiorsky, Kinetics of Human Motion. Champaign, IL: Human Kinetics, 32-35, V.M. 2001.

[36] Elliott, Bruce C., Jacqueline A. Alderson, and Eliot R. Denver. "System and modelling errors in motion analysis: Implications for the measurement of the elbow angle in cricket bowling." Journal of Biomechanics 40.12 (2007): 2679-2685.

[37] Davis III, Roy B., et Leardini A, Chiari L, Della Croce U, Cappozzo A.; Human movement analysis using stereophotogrammetry. Part 3. Soft tissue artifact assessment and compensation. Gait Posture. 2005 Feb;21(2):212-25.]:

[38] Leardini, Alberto, et al. "Human movement analysis using stereophotogrammetry: Part 3. Soft tissue artifact assessment and compensation." Gait & posture 21.2 (2005): 212-225.

[39] Smart-D, B. T. S. "High frequency digital system for biomechanical motion analysis." *BTS Bioengineering*.

[40] Petersen, Anne Berit, et al. "Factors associated with secondhand tobacco smoke in the home: an exploratory cross-sectional study among women in Aleta Wondo, Ethiopia." *BMC public health*16.1 (2016): 910.

[41] DeWitt, John K., et al. "Load Variation Influences on Joint Work During Squat Exercise in Reduced Gravity." (2011).

[42] Southwell, Daniel J., et al. "The effects of squatting footwear on three-dimensional lower limb and spine kinetics." Journal of Electromyography and Kinesiology 31 (2016): 111-118.

[43][M. Mansfield and C. O'Sullivan, *Understanding Physics, 2nd* Edition, (John Wiley&sons ,Ireland, 2011)

[44] Rao G, Amarantini D, Berton E, Favier D. 2006. Influence of body segments' parameters estimation models on inverse dynamics solutions during gait. J Biomech. 39(8): 1531–1536.

[45] Fregly, Benjamin J., Christopher D. Fregly, and Brandon T. Kim. "Computational prediction of muscle moments during ared squat exercise on the international space station." Journal of Biomechanical Engineering 137.12 (2015): 121005.

[46] Ravera, Emiliano Pablo, Marcos José Crespo, and Ariel Andrés Antonio Braidot. "Estimation of muscle forces in gait using a simulation of the electromyographic activity and numerical optimization." Computer methods in biomechanics and biomedical engineering 19.1 (2016): 1-12.