POLITECNICO MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

ARED Kinematics – Biomechanical quantification of bone and muscle loading to improve the quality of microgravity countermeasure prescription for resistive exercise

Tesi di Laurea Magistrale in
Biomedical Engineering - Ingegneria Biomedica

Author: **Elisabetta Marrucci**

Student ID: 907956
Advisor: Prof. Giancarlo Ferrigno
Co-advisors: Prof. Manuela Galli
Academic Year: 2022-23

Dedicated to my parents,

Abstract

ARED-Kinematics plans on improving the subject specific effectiveness of daily exercises on flight by estimating internal body loads; studying how kinematic data (SMART-DX) and estimation of internal bone and muscle forces developed during exercises in micro-gravity allow optimizing exercise programs in space and improving the knowledge of how resistance exercise in weightlessness affects the body. The present work hence focused on the following aims: (1) data collection using a motion capture (BTS SMART-DX) system and force plates during pre-flight; (2) biomechanical analysis regarding the Single leg squat, Normal Stance Squat, Wide stance squat, and Deadlift exercises; (3) statistical comparison of data collected. The exercise device used in the study is the Advanced Resistive Exercise Device (ARED) that allows astronauts to perform a wide variety of high-resistance exercises. Each exercise was repeated under three different levels of force at the level of the trapezius muscle thanks to the use of a bar. In particular, the questions that we imposed were:"How does the Ground Reaction Force evaluation change exercise by exercise and with respect to different levels of force?" "Are there any differences between the Ground Reaction Force obtained with exercises in pre-, in- and post-flight?". We need to hand up a few steps in order to study the evolution of the Ground Reaction Force. The signal from the data was characterized by noise; for this, we implemented a code on Phyton to figure out a good signal where it was possible to identify four main points. In order to obtain a statistical behaviour of the second peaks in the Ground Reaction Force, we calculated the average of the points that identified the curve and obtained the standard deviation between the three levels of force. With the calculation of the standard deviation, we obtained that the higher deviation is between the exercise with 101 force and the one with 103 force, since there is a higher difference in force for all the four exercises. However, maintaining the same level of force and comparing the different exercises, the higher deviation is between the Single leg squat and the others. This is why the type of exercise is completely different with the others since it uses one leg and not both. Instead, the other deviations are very similar and quite small.

Keywords: ARED-Kinematics, Space Medicine, biomechanics analysis, physical exercises

Sommario

ARED-Kinematics mira a migliorare l'efficacia specifica soggettiva degli esercizi quotidiani in volo stimando i carichi interni del corpo; studiando come i dati cinematici (SMART-DX) e la stima delle forze interne alle ossa e ai muscoli sviluppate durante gli esercizi in microgravità consentano di ottimizzare i programmi di allenamento nello spazio e migliorare la conoscenza su come l'esercizio di resistenza in assenza di gravità influenzi il corpo. Il presente lavoro si è quindi concentrato sugli obiettivi seguenti: (1) raccolta dati mediante un sistema di motion capture (BTS SMART-DX) e piattaforme di forza durante il pre-volo; (2) analisi biomeccanica riguardante gli esercizi di squat su una gamba, squat in posizione normale, squat a gambe divaricate e stacco da terra; (3) confronto statistico dei dati raccolti. Il dispositivo di allenamento utilizzato nello studio è il Advanced Resistive Exercise Device (ARED), che consente agli astronauti di eseguire una vasta gamma di esercizi ad alta resistenza. Ogni esercizio è stato ripetuto con tre diversi livelli di forza a livello del muscolo trapezio grazie all'uso di una barra. In particolare, le domande che ci siamo posti sono: "Come cambia la valutazione della forza di reazione al suolo esercizio per esercizio e in relazione a diversi livelli di forza?" "Ci sono differenze tra la forza di reazione al suolo ottenuta con gli esercizi prima, durante e dopo il volo?". Abbiamo dovuto compiere alcuni passaggi per studiare l'evoluzione della forza di reazione al suolo. Il segnale dei dati era caratterizzato da rumore; per questo motivo, abbiamo implementato un codice in Python per ottenere un buon segnale in cui fosse possibile identificare quattro punti principali. Per ottenere un comportamento statistico dei secondi picchi nella forza di reazione al suolo, abbiamo calcolato la media dei punti che identificavano la curva e ottenuto la deviazione standard tra i tre livelli di forza. Con il calcolo della deviazione standard, abbiamo ottenuto che la deviazione maggiore si verifica tra l'esercizio con forza 101 e quello con forza 103, poiché vi è una maggiore differenza di forza per tutti e quattro gli esercizi. Tuttavia, mantenendo lo stesso livello di forza e confrontando gli esercizi diversi, la deviazione maggiore si verifica tra lo squat su una gamba e gli altri. Questo perché il tipo di esercizio è completamente diverso dagli altri, poiché coinvolge una gamba sola e non entrambe. Invece, le altre deviazioni sono molto simili e piuttosto contenute.

Parole chiave: ARED-Kinematics, medicina spazile, analisi biomeccanica, esercizi fisici

Contents

Introduction

The allure of space exploration has demonstrated humanity's unwavering pursuit of the seemingly impossible. While the notion of studying distant planets once appeared implausible, the prospect of a Mars landing now stands as a tangible reality. Nevertheless, this ambitious endeavor is not without its challenges, particularly concerning astronauts' well-being and ability to adapt to a microgravity environment. Numerous adverse effects accompany life in a gravity-deprived setting, encompassing cardiovascular, respiratory, visual, and musculoskeletal complications. Among the significant concerns are Space Adaptation Syndrome, irregular ventilation, perfusion disparities, muscle deconditioning, atrophy, and bone demineralization. Consequently, various research initiatives have endeavored to replicate and analyze the specific environmental conditions encountered by space travelers. [7]

In scientific progress, computer simulations have emerged as a crucial tool, with software such as OpenSim playing a pivotal role in this context. To address deconditioning during long-duration missions (LDMs), astronauts diligently adhere to a specialized training protocol before, during, and after their spaceflight. Notably, all space companies and agencies use the International Space Station (ISS) to gain valuable insights into physiological countermeasures. Targeted cardiovascular and resistive training regimens are employed, employing specific exercise devices: CEVIS (Cycle Ergometer with Vibration Isolation and Stabilization) and the treadmill COLBERT are harnessed to maintain cardiovascular health, while the Advanced Resistive Exercise Device (ARED) effectively combats muscle atrophy and bone mineral loss. ARED's ingenious design facilitates the simulation of free weight exercises in microgravity, generating a constant load that can be adjusted from 0 to 272.5 Kg. The device boasts a repertoire of up to 29 exercises, including Single leg squat, Normal Stance Squat, Wide stance squat, and Deadlift. [14] Complementing this mechanical architecture is the state-of-the-art motion capture system known as BTS SMART-DX, responsible for gathering kinematic data through passive markers placed strategically on the cosmonauts' bodies. On board of the ISS, a 12-camera motion analysis system (BTS Bioengineering, SMART DX) collects the participant's motion history at 100 Hz. The system tracked the spatial position of spherical reflective markers, 10 mm in diameter, placed at key anatomical sites. The system was capoundsted within the participant's activity volume according to the manufacturer's procedures, the capoundstion error is <0.1 mm. A static pose of the participant is used to scale a biomechanical model to the participant's anthropometrics. BTS's SMARTtracker® and SMARTanalyzer® software programs are used to remove spurious marker trajectories, interpolate dropouts, and remove stray reflections using the manufacturer's recommended procedures. [16] - [17]

Before the BTS SMART-DX system, on board ELITE S2 was used. ELITE S2 is a payload of the Italian Space Agency (ASI) for quantitative human movement analysis in weightlessness. The ELITE S2 facility consists in a central unit (Interface Management Unit,IMU) for the electrical power distribution and the data handling and four video cameras mounted on the walls of the laboratory and connected by cables to the IMU. The instrument working principle is based on the shape detection of passive markers applied on the body, illuminated by infrared light and captured by the video cameras. For each experiment, a set of body landmarks are identified, and retro-reflective markers are attached to the astronaut operating the experiment. The astronaut performs prescheduled movements while the video cameras capture the trajectories of the body parts catching the light reflected by the markers. This allows the system to record the marker position and elaborate the movement's three-dimensional trajectory. [12] - [1]

This thesis is inserted in "ARED Kinematics – Biomechanical quantification of bone and muscle loading to improve the quality of microgravity countermeasure prescription for resistive exercise", which involves European Space Agency (ESA), Neuroengineering and Medical Robotics Laboratory (NearLab) and Posture and Movement Analysis Laboratory (Luigi Divieti) of Politecnico di Milano, Johnson Space Center (JSC) of National Aeronautics and Space Administration (NASA) and Kayser Italia. The project plans on improving the subject-specific effectiveness of daily exercises on flight by estimating internal body loads. The present work hence focused on the following aims: (1) data collection using a motion capture (BTS SMART-DX) system and force plates during pre-flight ; (2) biomechanical analysis regarding the Single leg squat, Normal Stance Squat, Wide stance squat, and Deadlift exercises; (3) statistical comparison of data collected.

1 | State of the Art

In this first chapter we will expose the current state of the art essential to understand the roots that led to the budding of the current project.

1.1. Physiological adaptations during long-term space mission

During the last decades, many experiments and analysis have been conducted on the physiological modifications related to microgravity environments. These studies were possible thanks to mankind aim of exploring the space around our planet. Humanity firstly started with missions around the Earth Orbit: just think about Yuri Gagarin, who completed in 1961 a single orbit of the Earth for the first time. After this important accomplishment, the idea of reaching farther distances became concrete and real. Therefore, short-term and, later, long-term spaceflight (typically six months) became feasible, implying a Wide variety of psychological and physical stressors on the body, including (but not limited to) sustained levels of ionizing radiation, circadian shifts, microgravity, diet restriction, sleep deprivation, reduced physical work, confinement and isolation. Space Motion Sickness is experienced by 60% to 80% of space travelers during their first 2 to 3 days in microgravity. It manifests clinically with symptoms similar to other forms of motion sickness (such as malaise, fatigue, loss of appetite, nausea and vomiting) and it is a branch of the Space Adaptation Syndrome. The latter also includes facial stuffiness from headward shifts of fluids, headaches, and back pain [5]. Among all the drawbacks and side effects while living in a place lacking gravity, we could list cardiovascular, respiratory, visual and musculoskeletal downsides.

Cardiovascular alterations from spaceflight begin immediately upon liberation from Earth's gravitational force. Prolonged exposure to microgravity and radiation yields profound effects on the cardiovascular system, including a massive cephalad fluid translocation and altered arterial pressure, which attenuate blood pressure regulatory mechanisms and increase cardiac output. Also, central venous pressure decreases due to the loss of venous compression.

Nowadays, a primary objective of international space programs is to install permanently manned bases on the Moon and to undertake manned explorations of Mars within the next 5-10 years. For these projects to become a reality, the negative effects of microgravity on the human muscle system must be overcome. Indeed, since the beginning of the space-flight era, weightlessness was shown to lead to substantial changes of muscle function. These changes, globally defined as deconditioning, consist mainly of loss of muscle mass, force and power, increased muscle fatigability, and abnormal reflex patterns [4]. They are due to a combination of factors, among which an increased degradation of muscle proteins and substantial changes of the neuromuscular control of movement (both brought about by the absence of the constant pull of gravity) play a major role. Uninterrupted bed rest was found to be a suitable model to simulate the decrease in proteins synthesis. The researchers showed a 50% reduction in skeletal muscle protein synthesis during the first two weeks of bed rest [4]. Hence, during long-term space missions, muscle deconditioning could limit the crews' ability to work in space (or on the Moon/Mars surface) and to rapidly egress the spacecraft in an emergency landing. Furthermore, muscle atrophy and weakness are of particular concern when the transition from zero to one g occurs, as the musculoskeletal system after several days/months in weightlessness has to bear suddenly the gravity force.

There exists very limited data for determining the effectiveness of human health and performance countermeasures intended to preserve astronaut health during long-duration space exploration missions. Exercise countermeasures used in the Space Shuttle Program and on the International Space Station do not eliminate bone loss or muscle deconditioning. Without an effective countermeasure, astronauts lose bone density at a rate of 1-2% a month, which may lead to early onset osteoporosis and place the astronaut at greater risk of fracture after returning to the earth's gravitational field. [4]

1.2. Exercises in the space environment

The International Space Station (ISS) (1.1) is a large spacecraft in orbit around Earth at an average altitude of approximately 400 kilometers and travels at 28,100 kmh. The first piece of ISS was launched in November 1998.

Figure 1.1: photograph of the International Space Station (ISS). Credits: NASA.

Nowadays, the International Space Station (ISS) serves as a home for crews of astronauts and cosmonauts, providing a unique environment for scientific research due to the presence of microgravity.

Microgravity is the condition in which people or objects appear to be weightless. In microgravity, astronauts can float in their spacecraft – or outside, on a spacewalk. Gravity is what holds the moon in orbit around Earth. Gravity causes Earth to orbit the sun. It keeps the sun in place in the Milky Way galaxy. Gravity, however, does become weaker with distance. It is possible for a spacecraft to go far enough from Earth that a person inside would feel very little gravity. But this is not why things float on a spacecraft in orbit. The International Space Station orbits Earth at an altitude between 320 and 400 kilometers. At that altitude, Earth's gravity is about 90 percent of what it is on the planet's surface. If 90 percent of Earth's gravity reaches the space station, the astronauts float there because they are in free fall. In a vacuum, gravity causes all objects to fall at the same rate. The mass of the object does not matter.

The ISS functions as a science laboratory where various fields of research are explored, including biology, life sciences, new technology development, astronomy, and Earth observation. The spacecraft, its crew and any objects aboard are all falling toward but around

Earth. Since they are all falling together, the crew and objects appear to float when compared with the spacecraft.

The construction and utilization of the ISS have been collaborative efforts involving several nations. Its assembly involved the astronauts directly assembling parts in space. The space station comprises three nodes: Node 1 (Unity) serves as a connection point between the U.S.A and Russian segments of the ISS, Node 2 connects the U.S.A, European, and Japanese laboratories, and Node 3 (Tranquility) provides habitation functions such as hygiene, sleeping, and training compartments. Node 3, built by the European Space Agency (ESA) and the Italian Space Agency (ASI), is the most modern section of the ISS and serves as the training area for station activities.

NASA utilizes the ISS to conduct experiments and learn more about living and working in a space environment. These valuable lessons will contribute to future missions that involve sending humans even farther from Earth than ever before. The ISS plays a crucial role in advancing our understanding of space exploration and human adaptation to long-duration space travel.

Exercise is an important part of the daily routine for astronauts aboard the International Space Station to prevent bone and muscle loss, and to maintain cardiovascular health. On average, astronauts exercise two hours per day. The equipment they use in space is different than what we use on Earth.

Here we can consider the most used exercise devices in the ISS:

Cycle Ergometer with Vibration Isolation System (CEVIS)

The Cycle Ergometer with Vibration Isolation and Stabilization (CEVIS) system is essentially a recumbent bicycle, which provides aerobic exercise that is used as a countermeasure to the harmful physiological effects of exposure to microgravity that are anticipated during stays on the ISS. CEVIS is operating in the United States Laboratory Module (US LAB) on the ISS since it was installed in 2001.

CEVIS is computer controlled and maintains an accurate workload independent of pedal speed. The ergometer contains the main mechanics and electronics. Friction and resistance are applied to an internal flywheel via a braking band, which is adjusted by a stepper motor. The stepper motor adjusts the tension in the braking band to maintain a constant workload independent of pedal speed.

An Inertial Vibration Isolation System (IVIS), consisting of a drive rod and throw masses, is used to stabilize the system by counteracting the motions generated by the crew member. Four wire rope isolators provide a structural attachment between the CEVIS frame and ISS to minimize the vibrations transmitted to the ISS structure. When not in use, the CEVIS system is rotated to a stowed configuration to minimize the protrusion into the ISS aisle. [10]

Figure 1.2: photograph of the Cycle Ergometer with Vibration Isolation System (CEVIS). Credits: NASA.

Combined Operational Load Bearing External Resistance Treadmill (COLBERT)

The Combined Operational Load Bearing External Resistance Treadmill (COLBERT) is the second treadmill on the International Space Station (ISS). It is a critical countermeasure device for maintaining crew health on-orbit and for preparing the crew for their return to the 1g environment on Earth.

COLBERT collects data that allow scientists and physicians to monitor the efficacy of the treadmill in providing intended workout intensities to the crew. It is designed to allow walking and running in a microgravity environment for maintaining crew cardiovascular fitness, muscular strength, and to exercise neurophysiological pathways and reflexes that are required to walk once returned to Earth. In addition, the treadmill minimizes the transfer of dynamic forces caused by the operation of the treadmill so that excessive loads are not transferred to the Space Station structure. [15]

Figure 1.3: photograph of the Combined Operational Load Bearing External Resistance Treadmill (COLBERT). Credits: NASA.

Advanced Resistive Exercise Device (ARED)

The Advanced Resistive Exercise Device (ARED) allows astronauts to perform a Wide variety of high-resistance exercises. To minimize force transmission to the ISS during exercise, the ARED can rotate and translate relative to the ISS via a vibration isolation system (VIS). During squat exercises, the astronaut holds the ARED shoulder bar across the shoulders while standing on the ARED footplate. Two vacuum cylinders then apply a compressive load to the astronaut between the shoulder bar and the footplate. Vacuum cylinder loads are typically set to an Earth-level value plus 70% of body weight (BW) to account for the lack of gravity. Though the ARED has been shown to be as effective as free weights for building muscle strength and volume on Earth, the extent to which ARED squat exercise on the ISS achieves Earth equivalent back and leg muscle moments remains unknown.

The first resistive device flow in the ISS was he interim Resistive Exercise Device (iRED). However, iRED is limited in the maximal loads that it can provide and thus, is viewed as an interim solution to the loss of muscular strength. Thus, NASA has initiated the design and construction of the Advanced Resistive Exercise Device (ARED) as a long-term solution to preserving muscle strength during extended habitation of microgravity environments.

Resistance is provided by the movement of pistons within the vacuum of the cylinders. The piston rods are attached to an arm base assembly, which acts as a lever arm when moving the main arm assembly. 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. 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. ARED can be configured to provide exercises using the lift bar or the exercise cable. It provides a load of up to 272 kilograms for bar and 113 kilograms for cable exercise and connects to a Space Station Computer (SSC) that makes it easier for crew members to follow a personalized exercise plan. [2]

Figure 1.4: photograph of the Advanced Resistive Exercise Device (ARED). Credits: NASA.

NASA and ESA researchers are working to lessen muscle atrophy and loss of bone density in astronauts involved in prolonged space flights. Both of these physical changes can be hazardous to astronauts on an extended exploration mission. Injured or weak crew members may not be able to perform their assigned tasks, causing safety concerns for themselves, as well as fellow astronauts. All crew members need to be in top physical condition to ensure the completion of the mission. Astronauts also need strong muscles and bones to perform tasks while exploring a lunar or Martian surface. They must be able to lift, bend, build, maneuver and even exercise during a mission. Both the moon and Mars have enough gravitational force to require strong muscles and bones to do these tasks. If a crew member happens to trip and fall, the strength of their muscles and bones can mean the difference between getting up and returning to work, or having to end the mission and return back to Earth. On Earth, the strength of muscles and bones is important to being physically fit and healthy. Severe muscle atrophy or bone loss in space could mean a crew member might fail to recover his or her pre-flight physical condition back on Earth. Therefore, astronauts do regular exercise and strength training before, during, and after a mission to keep their muscles and bones strong. Performing multi-joint weight-bearing exercises, such as the push-up for upper body strength and the squat for lower body strength, can help develop stronger muscles and bones. [8]

The Astronaut Strength, Conditioning, and Rehabilitation (ASCR) group is comprised of certified strength and conditioning coaches and licensed and certified athletic trainers. The ASCR group works within NASA's Space Medicine Division providing direction and supervision to the astronaut corp with regards to physical readiness throughout all phases of space flight. The ASCR group is overseen by flight surgeons with specialized training in sports medicine or physical medicine and rehabilitation. The goals of the ASCR group include: designing and administering strength and conditioning programs that maximize the potential for physical performance while minimizing the rate of injury; providing appropriate injury management and rehabilitation services; collaborating with medical, research, engineering, and mission operations groups to develop and implement safe and effective in-flight exercise countermeasures; providing a structured, individualized post-flight reconditioning program for long-duration crew members. [6]

The exercises commonly performed on the ISS during each astronaut's training session include the Single leg squat, Normal Stance Squat, Wide stance squat, and Deadlift. As previously mentioned, the ARED system enables space travelers to undergo extensive physical preparation, ensuring correct performance and avoiding any injuries or inefficacies in their workout routines. A practical explanation of the optimal techniques for these exercises is provided below. It is important to note that the exercises and their execution are reviewed and approved by the NASA Astronaut Strength, Conditioning, and Rehabilitation (ASCR) specialists.

Single leg squat

The Single leg squat is an effective exercise used to enhance lower limb strength and stability, particularly in the quadriceps, glutes, and hip muscles. However, improper execution can lead to potential risks such as knee and ankle injuries.

The optimal Single leg squat technique requires starting in a standing position with one leg lifted off the ground, ensuring the other leg is firmly planted on the floor. The grounded foot should be positioned directly under the hip. The arms can be extended forward for balance, while maintaining an upright and neutral position of the spine.

In the initial phase, slowly lower the body by bending the knee of the ground leg. The motion should be controlled and balanced, ensuring that the knee tracks in line with the toes to avoid excessive inward or outward movement.

While descending, aim to reach a knee flexion angle of approximately 90 degrees or more. At the lowest point of the squat, the knee should be in line with your toes and your hip should be flexed to achieve a balanced position. [3]

Figure 1.5: lateral views of the correct squat position.

Normal stance squat and Wide stance squat

The Normal Stance Squat, a fundamental exercise used in both training and rehabilitation, effectively strengthens lower limb muscles and assesses ranges of motion. This closed kinetic chain motion task involves coordinated movements of the hips, knees, and ankles. It requires the recruitment and synergy of several muscle groups, with contractions and relaxations occurring in specific phases. The squat starts from a standing position, maintaining a straight trunk, and the knees are flexed to achieve an angle equal to or greater than 90°. After knee extension, the starting position is regained.

On the other hand, the Wide stance squat is a variation of the Normal Stance Squat. It engages more muscles compared to the former. In the Wide stance squat, the feet are placed farther apart (1.5-2 times Wider separation) than in the Normal Stance Squat, which has a foot placement similar to shoulder width. However, improper execution of both squat variations can lead to training inefficiency and various injuries, particularly affecting the trunk and lower limb joints.

To minimize the risk of injuries and ensure optimal activation of lower limb muscles during squats, it is crucial to follow an appropriate technique (as depicted in 1.6). This includes keeping the heels in contact with the floor to prevent forward leaning of the trunk, maintaining an upright trunk with a slightly lordotic lumbar spine (pelvic anteversion) for a neutral spine position, ensuring that the knees track over the toes to avoid bringing them closer or moving beyond the vertical lines of the toes, and keeping the tibiae parallel to the upright torso. Additionally, maintaining a forward or upward gaze during the squat is recommended. [9] - [11]

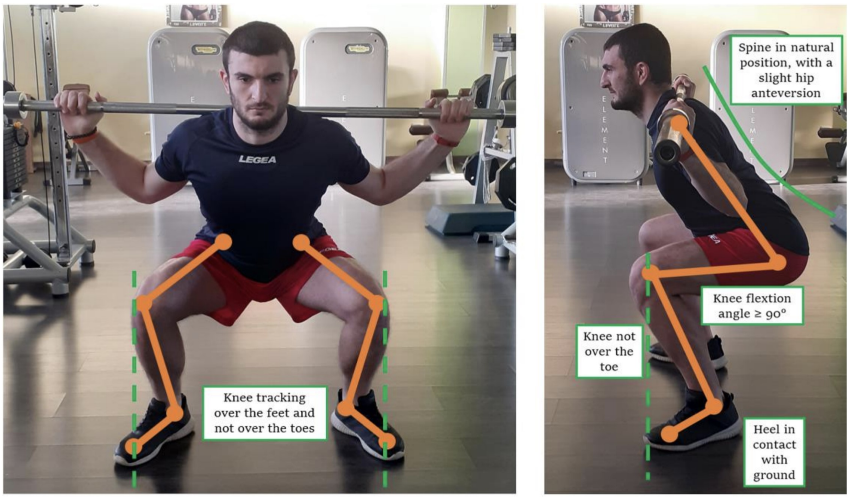

Figure 1.6: frontal and lateral views of the correct squat position. Dashed green vertical lines originate from the toes. In the frontal plane, knee joints remain laterally with respect to the lines; in the sagittal plane, they stay behind the lines. The solid green line highlights the natural lordotic lumbar curve, which has to be maintained during squatting. The knee angle should be $\geq 90°$.Credits: Mattia Quaranta and Marco Sinatra.

Deadlift

The Deadlift is a well-known training exercise commonly used to build strength in the trunk muscles. However, performing this complex motion incorrectly can pose a high risk of back injuries. To ensure safe and effective Deadlifts, it is essential to follow the optimal technique.

The ideal Deadlift technique involves starting in a partial squat position with feet at a natural width and arms positioned outside the legs, reaching down to grip the bar. Then, the hips and shoulders should be lifted simultaneously while maintaining the spine's natural alignment.

Similar to the squat exercise, certain rules should be followed to prevent training inefficiency and injuries during the Deadlift:

1. The hip joints must be higher than the knees to avoid forward leaning of the trunk. 2. Keep an upright trunk to maintain a neutral position of the spine. 3. Slightly adduct the shoulder blades in front of the bar. 4. Gaze forward during the lift. 5. Ensure that the knees track over the toes, preventing them from coming closer or going beyond the vertical lines of the toes themselves. By adhering to these guidelines, individuals can minimize the risk of back injuries and achieve the maximum benefits from Deadlift training. [18]

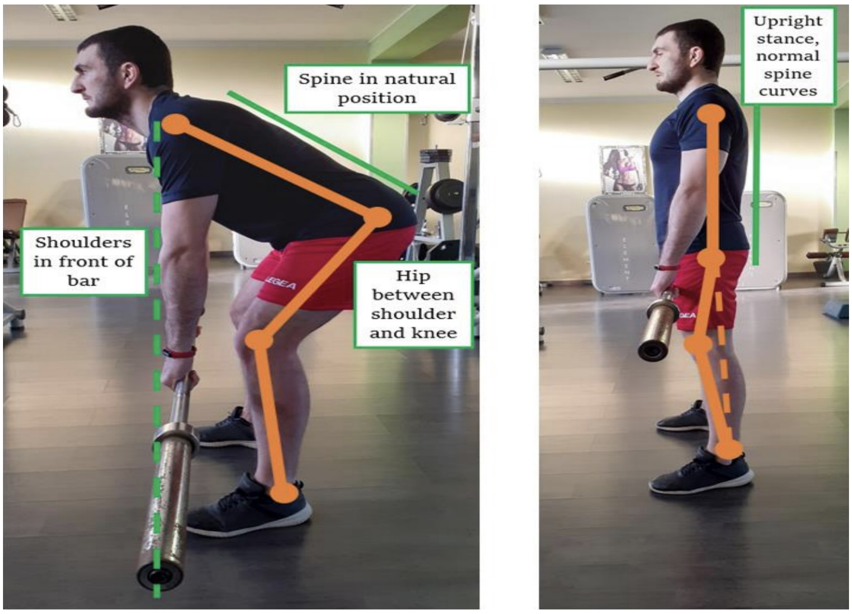

Figure 1.7: lateral view of correct starting and ending positions of Deadlift. The dashed green vertical line originates from the shoulder: the bar must not pass that boundary line. The solid green line shows the correct upright position of the trunk to be maintained during lifting. The dashed orange line, instead, points out the correct alignment of the shoulder, hip, and knee at the end of the exercise. Credits: Mattia Quaranta and Marco Sinatra.

1.3. Aim of the thesis

The thesis is inserted in "ARED Kinematics – Biomechanical quantification of bone and muscle loading to improve the quality of microgravity countermeasure prescription for resistive exercise", which involves the European Space Agency (ESA), Neuroengineering and Medical Robotics Laboratory (NearLab) and Posture and Movement Analysis Laboratory (Luigi Divieti) of Politecnico di Milano, Johnson Space Center (JSC) of National Aeronautics and Space Administration (NASA) and Kayser Italia. ARED-Kinematics plans on improving the subject specific effectiveness of daily exercises on flight by estimating internal body loads; studying how kinematic data (SMART-DX) and estimation of internal bone and muscle forces developed during exercises in microgravity allow optimizing exercise programs in space and improving the knowledge of how resistance exercise in weightlessness affects the body.

The protocol involved a subject who performed four exercises (Single leg squat, normal stance squat, Wide stance squat and Deadlift) in ARED at Jonson Space Center, Houston. Each exercise was repeated under three different levels of force at the level of the trapezius muscle thanks to the use of a bar.

The aim of the thesis is to visualize and evaluate the following parameters obtained from the experiment:

- Ground Reaction Force
- Rotational Arm Position
- Bar Angle Position
- Center of Pressure
- Bar Height

In particular, the questions that we imposed were: " How does the Ground Reaction Force evaluation change exercise by exercise and with respect to different levels of force?" "Are there any differences between the Ground Reaction Force obtained with exercises in pre-, in- and post-flight?".

In order to answer these questions, we consider especially the two peaks (one big and one small) that characterized the evolution of this parameter. The Ground Reaction Force curve strongly depends on the squats technique. In the case of unprofessionally performed squats we are not going to recognize the small peak because the flexion during the squats was not done properly. Namely, the person performing the squats can fully straighten or partially straighten the legs at the end of the ascending phase of the squat (during body lifting). For each exercise, we identified the small peak and compared them in a statistical and descriptive way to highlight the differences.

2 | Materials and Methods

Let's move on, therefore, to understand more specifically the conceptual path that led to the completion of the whole project. The following chapter will introduce the experiment's protocol and how the data were processed.

2.1. Protocol

The aim of this thesis is to visualize and evaluate different parameters obtained from four exercises by a subject. The thesis is inserted in "ARED Kinematics – Biomechanical quantification of bone and muscle loading to improve the quality of microgravity countermeasure prescription for resistive exercise", which involves the European Space Agency (ESA), Neuroengineering and Medical Robotics Laboratory (NearLab) and Posture and Movement Analysis Laboratory (Luigi Divieti) of Politecnico di Milano, Johnson Space Center (JSC) of National Aeronautics and Space Administration (NASA) and Kayser Italia. ARED-Kinematics plans on improving the subject specific effectiveness of daily exercises on flight by estimating internal body loads; studying how kinematic data (SMART-DX) and estimation of internal bone and muscle forces developed during exercises in microgravity allow optimizing exercise programs in space and improving the knowledge of how resistance exercise in weightlessness affects the body.

The protocol involved a subject who performed four exercises (Single leg squat, normal stance squat, Wide stance squat and Deadlift) in ARED at Jonson Space Center, Houston. Each exercise was repeated five times, and under three different levels of force at the level of the trapezius muscle thanks to the use of a bar.

The table below reports the identification name for each exercise used in the NASA protocol and during the Results and Discussion chapter.

Exercise	Code
Single leg squat	**EXID-6**
Normal stance squat	**EXID-1**
Wide stance squat	**EXID-32**
Deadlift	**EXID-2**

Table 2.1: The first column reports the four exercises and the second column reports the code identification.

The table below reports the identification code for the three levels of force applied to the trapezius muscle.

Force [lb]	Force [N]	Code
50	222	**101**
60	267	**102**
70	311	**103**

Table 2.2: The first column reports the force in pounds, the second column reports the force in Newton and the first column represents the code identification.

The whole project consists of obtaining some parameters during the performance of the exercises from a subject on the ground.

Here we are going to indicate the parameters extracted from the experiment:

- The main parameter that will be the focus of this thesis is the Ground Reaction Force. Ground Reaction Force (Ground Reaction Force) is a biomechanical term used to describe the force exerted by the ground on a body in contact with it. When a person stands, walks, runs, or jumps, their feet or the point of contact with the ground experience a force from the ground pushing back against the body's movement. The Ground Reaction Force can be broken down into three components: vertical component (Fz), which acts perpendicular to the ground surface and supports the body's weight. It opposes the force of gravity and keeps the person or object from falling through the ground; anterior-posterior component (Fx), which acts horizontally in the direction of the body's forward or backward movement. When walking or running, this component helps propel the body forward; medial-lateral

Component (Fy), which acts horizontally in the direction of the body's sideways movement. It is responsible for controlling side-to-side movements during activities like walking or running.

The Ground Reaction Force is typically measured using force plates or force sensors embedded in the ground or floor. These devices record the magnitude and direction of the force exerted on them by the body in contact with the ground.

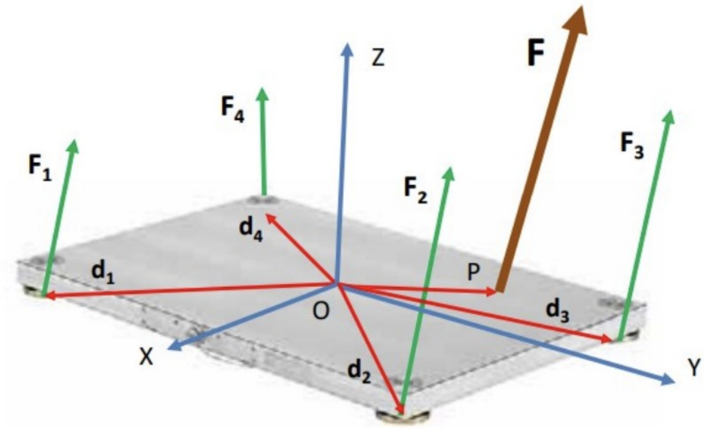

Figure 2.1: Force plate, which is characterized by four force sensors at the corner of the platform.

Understanding the Ground Reaction Force is crucial in biomechanics and sports science, as it provides valuable information about how forces interact with the body during different activities, helping to optimize performance, prevent injuries, and improve techniques in various movements. The Advanced Resistive Exercise Device (ARED) is composed by a force plate at the level of the feet.

- Rotational Arm Position and Bar Angle Position. The first parameter refers to the motion of the arm, and the second refers to the motion of the bar, and both are strictly connected with the performance of the exercise. Initially, the subject grasps the barbell with an overhand grip, while the bar position doesn't change, but the arm position changes in order to have a most efficient hold. The barbell is secured across the front of the shoulders, held in place by the fingers, hands, and the shelf created by lifting the elbows. During the descent and ascent phase of the squat, the two parameters are coherent with each other because: during the flexion, the body goes low, so the two positions decrease with respect to the flexion of the knees, and during the extension, the body goes up and the two position increase until reaching the stand position.

- Center Of Pressure along x and y. The Center of Pressure (COP) is the point of application or the resultant location of the Ground Reaction Force acting on a body in contact with a supporting surface, such as the floor or the ground. It represents the average point where all the vertical Ground Reaction Forces the body applies converge. The COP is a two-dimensional point typically expressed in the horizontal plane. The COP is an important parameter for assessing the stability and balance of a person during various movements. It provides insights into how the body adjusts its position to maintain equilibrium. As the Ground Reaction Force, also the Center Of Pressure is measured using the force platform.
- Bar Height. The bar height is an important parameter to visualize and study the behavior of the Ground Reaction Force during the exercises. During the study, we couldn't have access to the video of the subject, and this parameter helped us to understand the different phases of the squat and the different levels of flexion.

2.2. Data processing

The raw data used in the current work come from the experiment at Jonson Space Center. In order to study and visualize the evaluation of the different parameters for each exercise, some tools were used. Since the data of the rotational arm position, bar angle position and bar height were not characterized by noise, we plotted the graphs using the graph function of Excel.

As we have already mentioned, the focus of the thesis is the evolution of the Ground Reaction Force because later on, we would compare it with the same data but from the International Space Station. In this case, the raw data were made with noise, and to delete it, we used a code in Python. With the correct level of filtration, we could smoothly obtain the different peaks of the Ground Reaction Force that characterized the extension and flexion phases.

In order to check the resistance, it is important to consider the forced vibrations of the structure caused by dynamic loads generated during different types of movements. In the following figures, two different examples of the Ground Reaction Force curves generated during successive rhythmically performed squats are presented. The Ground Reaction Force curve strongly depends on the squats technique. In the case of unprofessionally performed squats (squats performed without experiences in sport exercises, without special training), two important differences in squat technique can occur. Namely, the person performing the squats can fully straighten or partially straighten the legs at the end of the ascending phase of the squat (during body lifting). This feature leads to significant differences in the graph of the Ground Reaction Force function. [13]

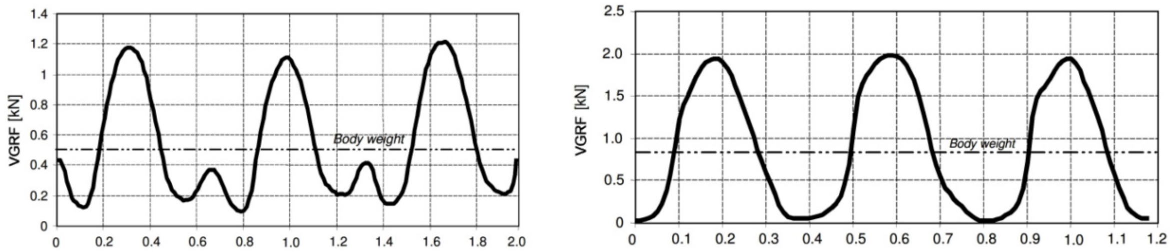

Figure 2.2: Examples of the Ground Reaction Force generated: on the right, during squats with fully straightened legs at the end of ascending phase of the squat; on the left squats with partially straightened legs during ascending phase of the squat.

Complete legs straightening at the end of ascending phase of the squat is possible during squats performed at slow and medium speeds. In the case of squats performed with the fully straightened legs the Ground Reaction Force curve is not an ideal sinusoid. The ideal sine curve is disturbed by the occurrence of small peak at the end of the squat period between two successive squats. It can be seen that the magnitude of the small peak does not achieve the value of body weight. In the case of squats performed with only partially straightened legs during the ascending phase (legs are slightly bent, body motion is smooth and similar to motion of the mass on the spring) the Ground Reaction Force curve is more or less a sine curve.

As we are going to see in the Result and Discussion chapter, also in our Ground Reaction Force data, we have the big peak and the small peak. Our main question is if we will distinguish the two peaks in the ISS, and for this reason, we will study how the peaks change with respect to the different exercises and the different levels of force.

Always using Python, we recognized four points in the Ground Reaction Force:

- X RED identifies the maximum value on the big peak
- X ORANGE identifies the maximum value on the small peak
- O RED identifies the minimum value before the X ORANGE point
- O ORANGE identifies the minimum value after the X ORANGE point

Here we can see just an example of the evolution of the Ground Reaction Force with the four points recognized:

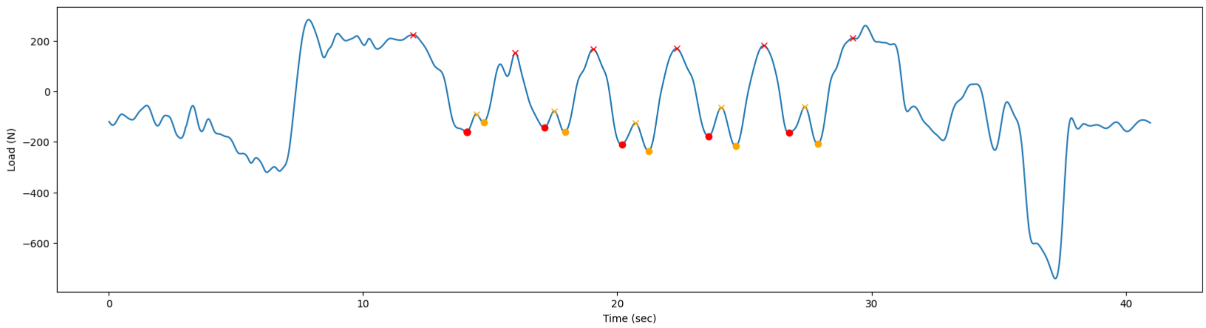

Figure 2.3: Ground Reaction Force curve with the four main points.

Last but not least, we tried to study the Center of Pressure either with Excel and Python, but because of the noise or other problems from the experiment, we couldn't extract any important data.

3 | Results and Discussion

Here, we are going to consider the results of the parameters extracted from the sensors exercise by exercise. Along the presentation of the results, they are combine with a discussion paragraph.

Before starting, we want to have a recap of the main abbreviations that we will use in the next chapters.

The table below reports the identification name for each exercise used in the NASA protocol.

Exercise	Code
Single leg squat	**EXID-6**
Normal stance squat	**EXID-1**
Wide stance squat	**EXID-32**
Deadlift	**EXID-2**

Table 3.1: The first column reports the four exercises and the second column reports the code identification.

The table below reports the identification code for the three levels of force applied to the trapezius muscle.

Force [lb]	Force [N]	Code
50	222	**101**
60	267	**102**
70	311	**103**

Table 3.2: The first column reports the force in pounds, the second column reports the force in Newton and the first column represents the code identification.

3.1. Single leg squat

3.1.1. Ground Reaction Force

We need to hand up a few steps in order to study the evolution of the Ground Reaction Force. The signal from the data was characterized by noise; for this, we implemented a code on Phyton to figure out a good signal where it was possible to identify four main points:

- X RED identifies the maximum value on the big peak
- X ORANGE identifies the maximum value on the small peak
- O RED identifies the minimum value before the X ORANGE point
- O ORANGE identifies the minimum value after the X ORANGE point

Since the Single leg squat exercise was done for three different levels of force applied to the trapezius muscle, we are going to visualize the evolution of the Ground Reaction Force signal for each level.

101 level force

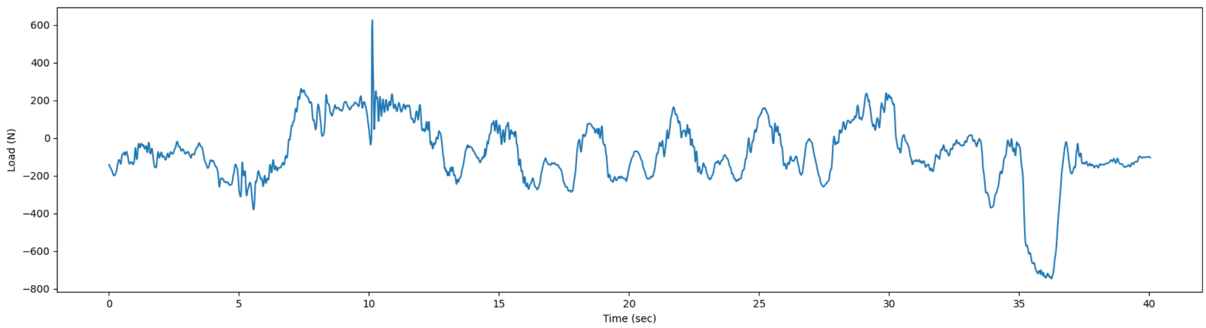

Figure 3.1: Ground Reaction Force original signal for Single leg squat with 101 level of force.

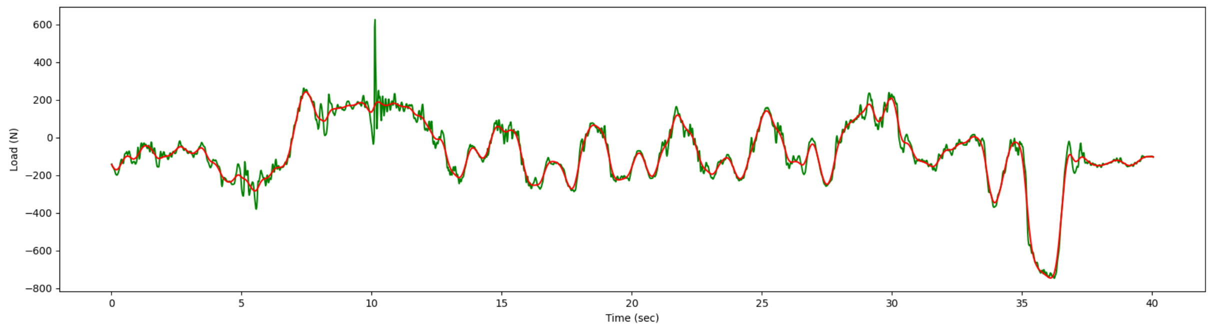

Figure 3.2: In green is the Ground Reaction Force original signal and in red is the Ground Reaction Force filtered signal.

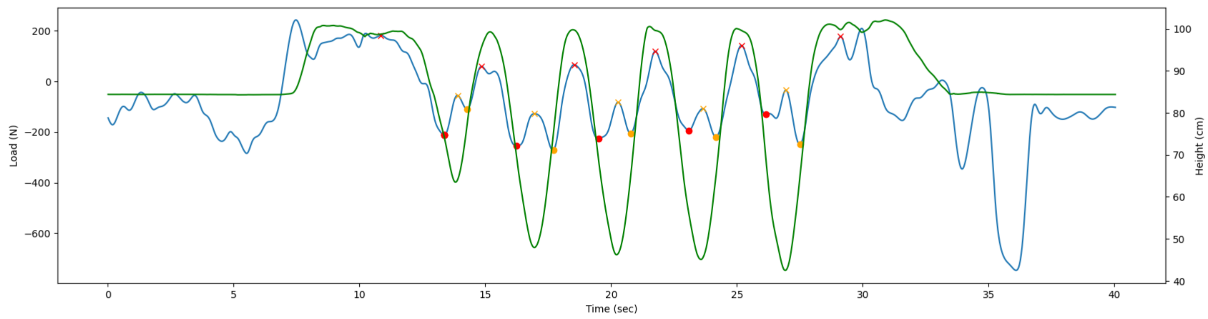

Figure 3.3: In blue the evolution of the load with 101 force, in green the evolution of the bar height with 101 force, x RED the maximum peaks, x ORANGE the second maximum peaks because of the contraction of the muscle, o RED the minimum peaks after the maximum peaks (x RED) and, o ORANGE the minimum peaks after the second maximum peaks (x ORANGE).

102 level force

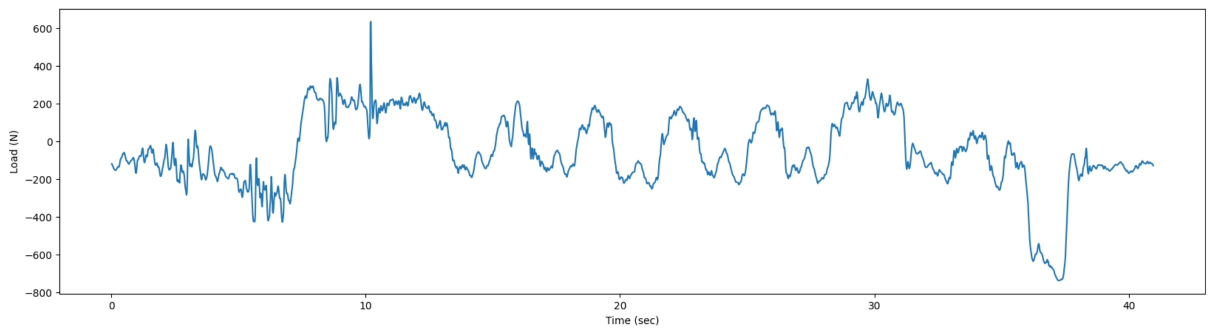

Figure 3.4: Ground Reaction Force original signal for Single leg squat with 102 level of force.

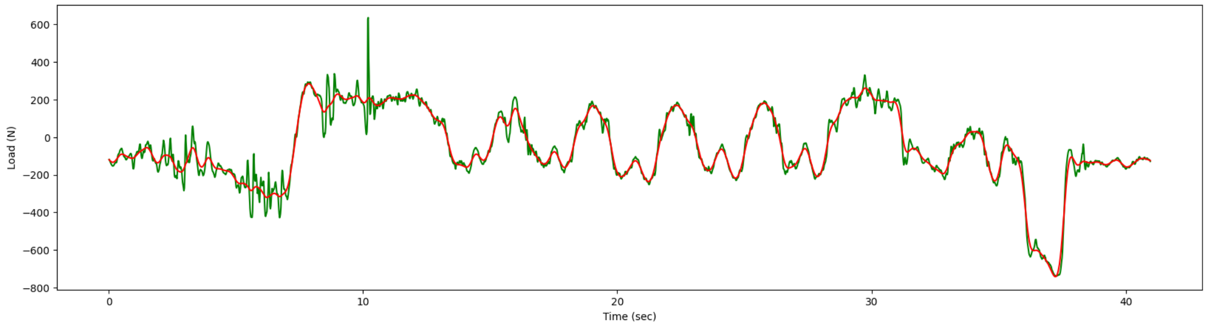

Figure 3.5: In green is the Ground Reaction Force original signal and in red is the Ground Reaction Force filtered signal.

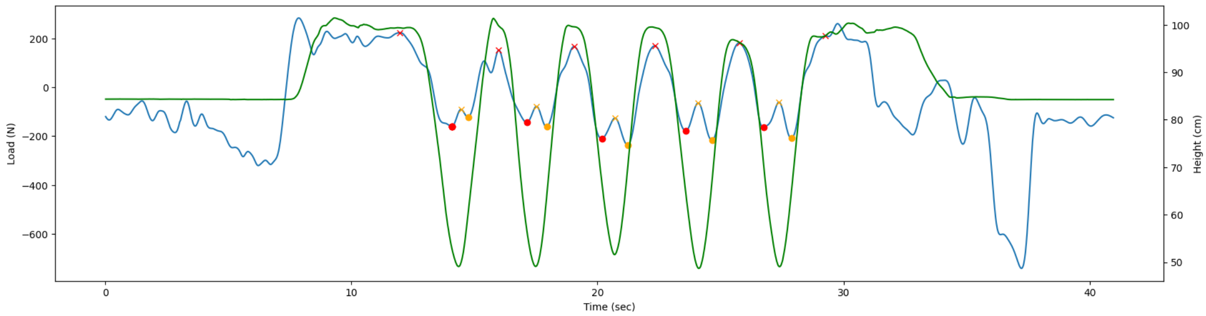

Figure 3.6: In blue the evolution of the load with 102 force, in green the evolution of the bar height with 102 force, x RED the maximum peaks, x ORANGE the second maximum peaks because of the contraction of the muscle, o RED the minimum peaks after the maximum peaks (x RED) and, o ORANGE the minimum peaks after the second maximum peaks (x ORANGE).

103 level force

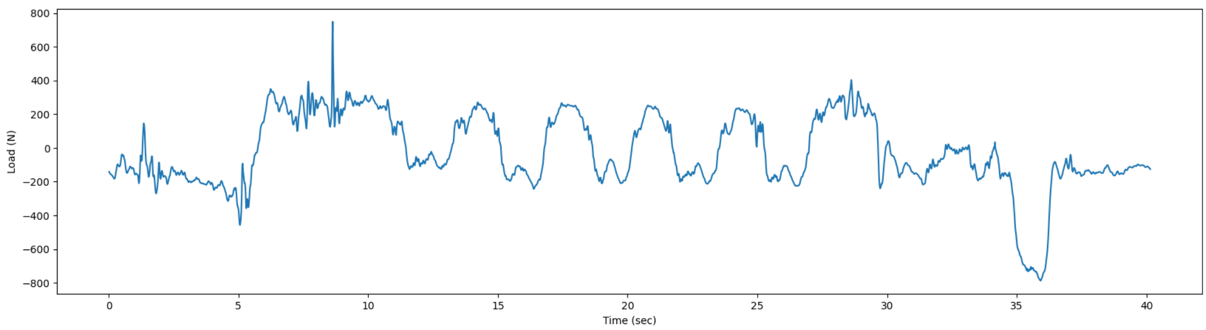

Figure 3.7: Ground Reaction Force original signal for Single leg squat with 103 level of force.

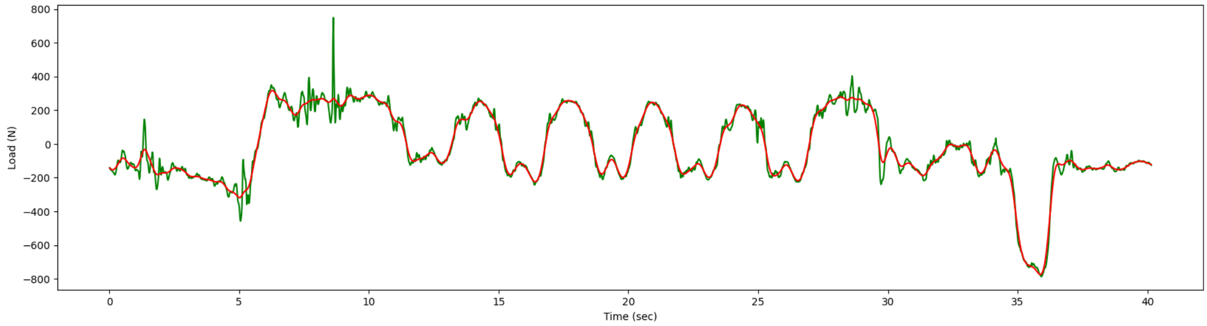

Figure 3.8: In green is the Ground Reaction Force original signal and in red is the Ground Reaction Force filtered signal.

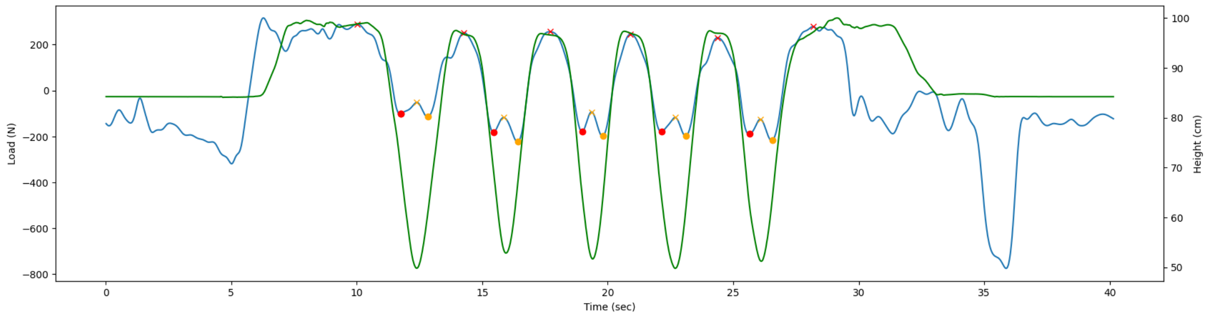

Figure 3.9: In blue the evolution of the load with 103 force, in green the evolution of the bar height with 103 force, x RED the maximum peaks, x ORANGE the second maximum peaks because of the contraction of the muscle, o RED the minimum peaks after the maximum peaks (x RED) and, o ORANGE the minimum peaks after the second maximum peaks (x ORANGE).

Explanation of the Ground Reaction Force

We want to focus our attention on the last graph for each level of force, see Figure 3.3, Figure 3.6 and Figure 3.9. The blue line is the evolution of the Ground Reaction Force, and in the same graph is also plotted the Bar Height signal to understand the timing of the exercise. The subject starts by standing up, where the GFR is high. While knee flexion exists, the Ground Reaction Force decreases until a minimum point, identified in the graph as o RED, such as the minimum peak after the maximum peak (x RED). During the flexion, the muscles acting are the hamstrings and adductors. Between the flexion and extension movement, we can consider a second peak (identified with the x ORANGE point) due to the inertial force and co-contraction of the muscles (see Materials and Methods chapter). During the extension, the quadriceps and gluteal muscles work until the maximum peak, identified by the x RED point in the graph. We are considering the

Single leg squat, where the small peaks (identified by the o RED, x ORANGE, and o ORANGE points) are at the end of the flexions.

3.1.2. Bar Height

Since the Bar Height signal is already reported with the Ground Reaction Force evolution, see Figure 3.3, Figure 3.6 and Figure 3.9, in this section we want to focus on the maximum and minimum values of the Bar Height for the three level of forces.

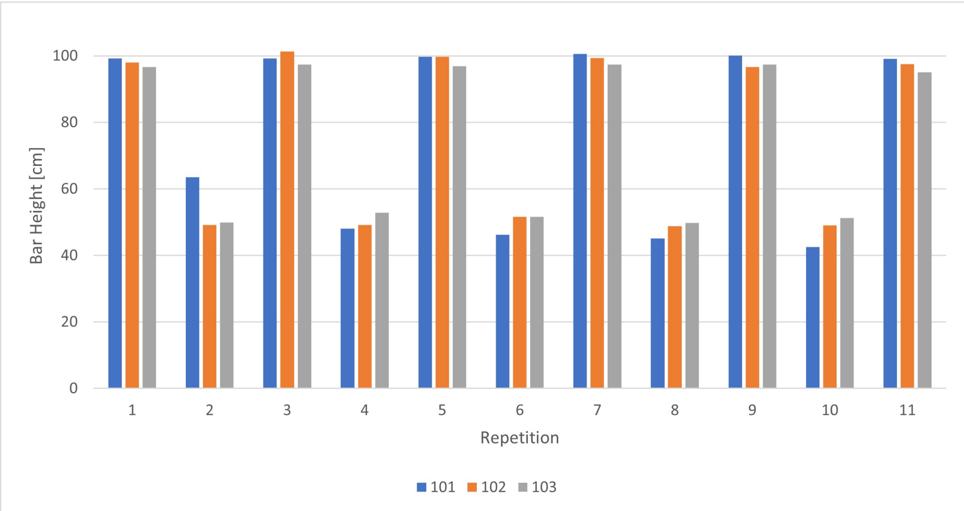

Figure 3.10: In blue the Bar Height values with 101 force, in orange the Bar Height values with 102 force, and in grey the Bar Height values with 103 force.

We can consider that the maximum values of the Bar Height for all three levels of force are very similar to each other for all the repetitions. It means that the subject returns at the same level at the end of the extension. Instead, the minimum values of the Bar Height are not so constant between the three different exercises, and especially for the exercise with 101 force, these values are different concerning the different repetitions. It means that the subject doesn't have the same knee flexion for all the repetitions. In the Discussion of the Single leg squat section, we will consider how these differences are important to understand the different evolution of the Ground Reaction Force considering the three levels of force.

Relationship between Ground Reaction Force and Bar Height

One of the main aims of the thesis is to study how the two peaks that characterized the Ground Reaction Force behave, changing along the different type of exercise and level of force.

First, we focus on the second peak, the small one designed by o RED, x ORANGE, and o ORANGE points. As already described in the Materials and Methods section, the presence of the second peaks is due to inertial force and the co-contraction of the muscles because the subject changes movement. In the Single leg squat, the second peak is while changing movement from flexion to extension at the level of the minimum values of the Bar Height. We visualized a strong relationship between the values of the second peaks with the values of the Bar Height. We thought that, in general, with a higher force, the second peaks should be higher than the ones with an lower force. So, we could expect that the second peak for the exercise with 103 level of force should be higher than the other two, and the second peak for the exercise with 102 level of force should be higher than the ones with 101 level of force. Regarding the Ground Reaction Force for the Single leg squat, the values of the second peaks are negative, it means that the exercise with 101 level of force should be higher than the other two, and the second peak for the exercise with 102 level of force should be higher than the ones with 103 level of force.

However, if we plot the second peaks repetition by repetition, we can see that not for every repetition, the levels of the peaks are coherent with what we expected. Here we reported the graphs:

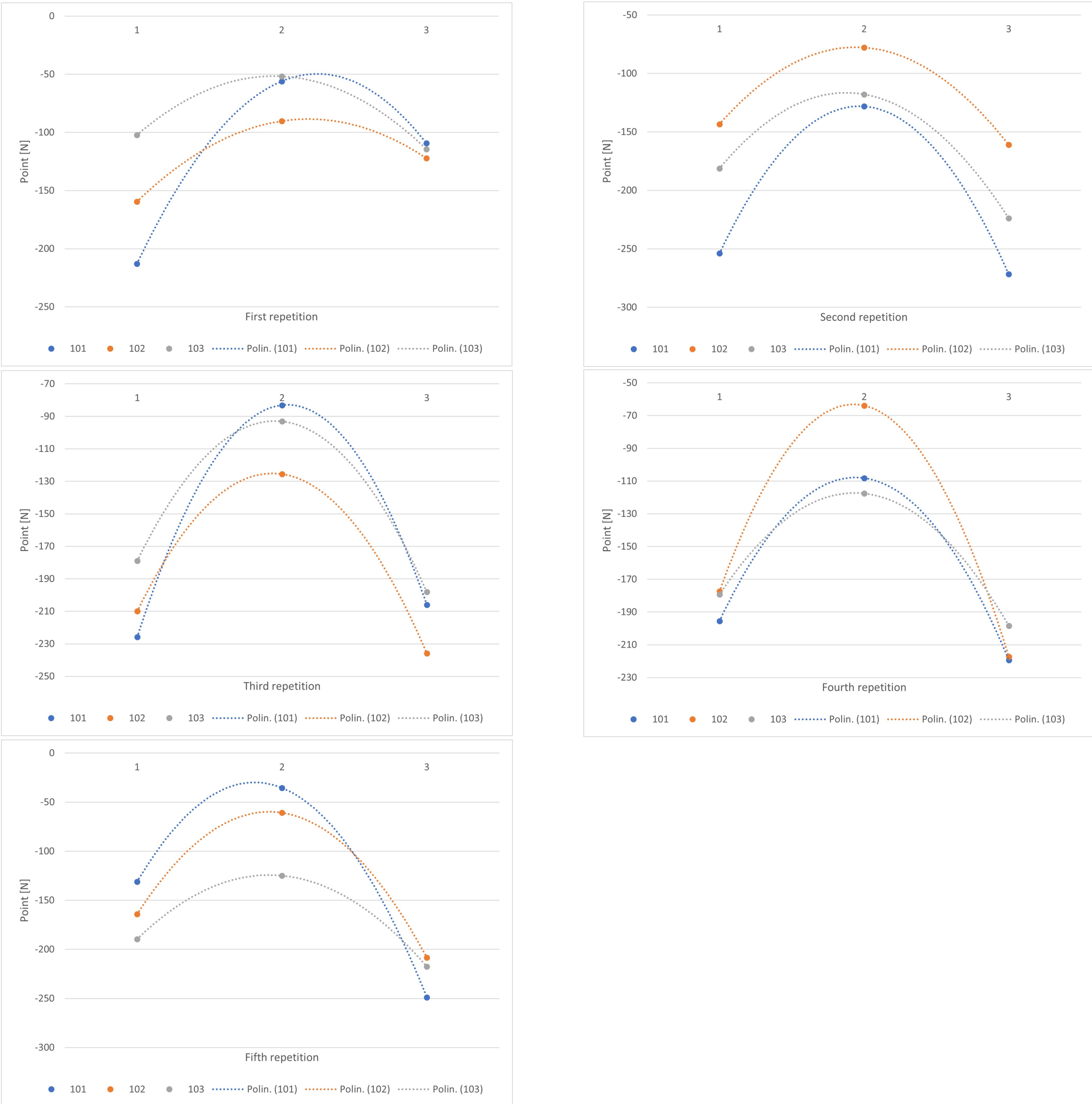

Figure 3.11: Considering each repetition, in blue the second peak of the Ground Reaction Force with 101 force, in orange the second peak of the Ground Reaction Force with 102 force, and in grey the second peak of the Ground Reaction Force with 103 force.

The behavior of the second peaks are not the same for all the repetitions because of the different flexions made by the subject. As we can see in Figure 3.10, the subject reaches different levels of flexions for the different repetitions during the same exercise. It is normal that the minimums Bar Height are different with respect to the different levels of force, but we would like to obtain the same minimums Bar Height during the same exercise. The subject doesn't have a target to reach while the flexions, it can be a problem to figure out a repeatable behavior of the second peaks of the Ground Reaction Force.

As explained in the Materials and Methods section, if a person performs a squat with a quick and explosive movement, the quadriceps muscles may contract rapidly and generate a secondary peak in the force curve. Alternatively, if a person performs a squat with a slower and more controlled movement, the hamstrings and gluteal muscles may contract more gradually, resulting in a smoother and more gradual decrease in the Ground Reaction Force.

To study this behavior, we calculate the difference between the maximum point (x RED) and the second maximum point (x ORANGE) identified in the Ground Reaction Force. In the graph below, we want to do a comparison of this difference with respect to the three levels of force used for the exercise.

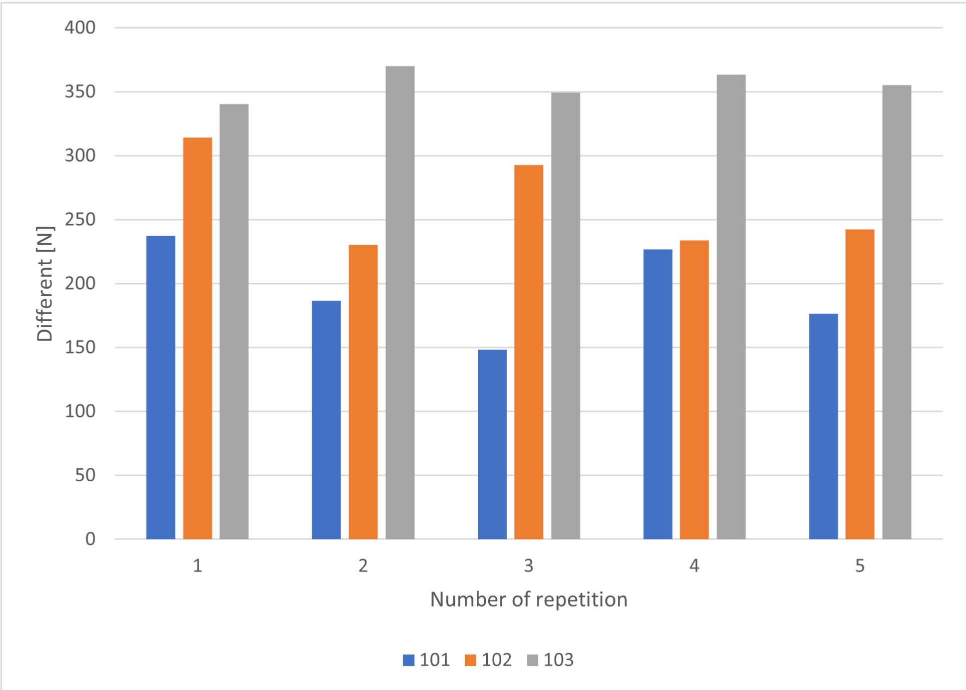

Figure 3.12: In blue the difference between x RED and x ORANGE with 101 force, in orange the difference between x RED and x ORANGE with 102 force, and in grey the difference between x RED and x ORANGE with 103 force.

The higher the distance, the lower the x ORANGE point, which means that the second peaks are lower. From this result, we can say that the distances are in general higher for the 103 level of force because the squat is more quick and explosive, having a higher force. Instead, the distances are in general lower for the 101 level of force because the squat is slower and more controlled due to the lower force.

Another important parameter to take into consideration is the height in terms of the Ground Reaction Force of the first peak, indicated by the x RED point. There is this peak at the end of the extension, and as we could expect, the exercise with 103 level of force has higher values of x RED points because there is more weight. As we saw in Figure 3.10, the level of the extension doesn't change with respect to the level of force, it means that the x RED values don't depend on the Bar Height. Here are reported the x RED evolution:

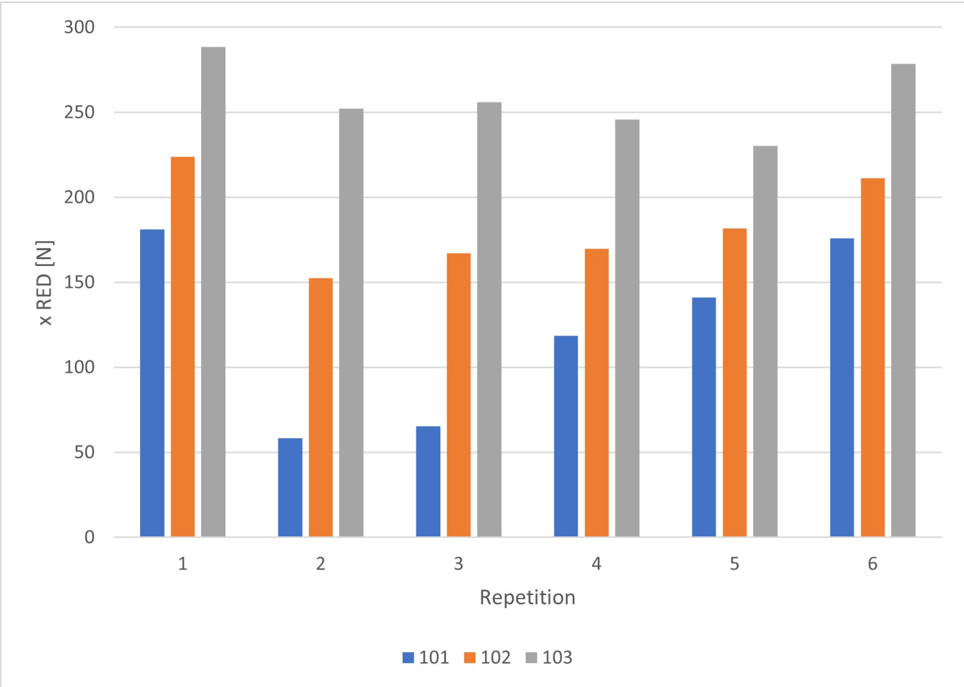

Figure 3.13: In blue the x RED peak with 101 force, in orange the x RED peak with 102 force, and in grey the x RED peak with 103 force.

Deviation of the second peaks concerning the level of the force

In order to obtain a statistical behavior of the second peaks in the Ground Reaction Force, we calculated the average of the points that identified the curve and obtained the standard deviation between the three levels of force. With this approach, we can evaluate how the Ground Reaction Force changes facing the same exercise but having different forces at the level of the trapezius muscle.

In the tables below, we reported the averages and the standard deviation of the three points that define the second peaks depending on the level of force.

	o RED	x ORANGE	o ORANGE
101 force [N]	-203,82± 45,93	-82,20± 37,61	-211,02± 62,36
102 force [N]	-170,846±25,01	-83,67±26,18	-188,98± 46,43
103 force [N]	-166,21±36,05	-101,04±30,09	-190,4673578±44,04

Table 3.3: Considering the three levels of the force, the table reports the average (first number) and the standard deviation (second number) of the three points that define the second peaks.

To visualize better the evolution of the point values that identify the second peak, we plotted the following graph:

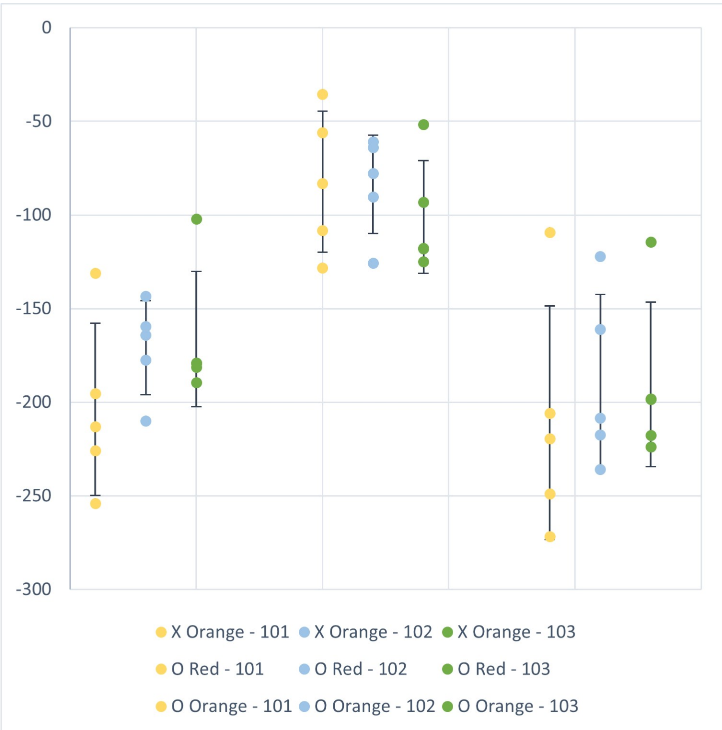

Figure 3.14: The graph reports in yellow the points obtained from the exercise with 101 level of force, in blue the points from the 102 level of force and in green the points from the 103 level of force. The first column represents the O RED points, the second column represents the X ORANGE points and the third column represents the O ORANGE points. The black lines indicate the standard deviation of each point from their average.

Using the average values, we plotted the average second peaks for the Single leg squat:

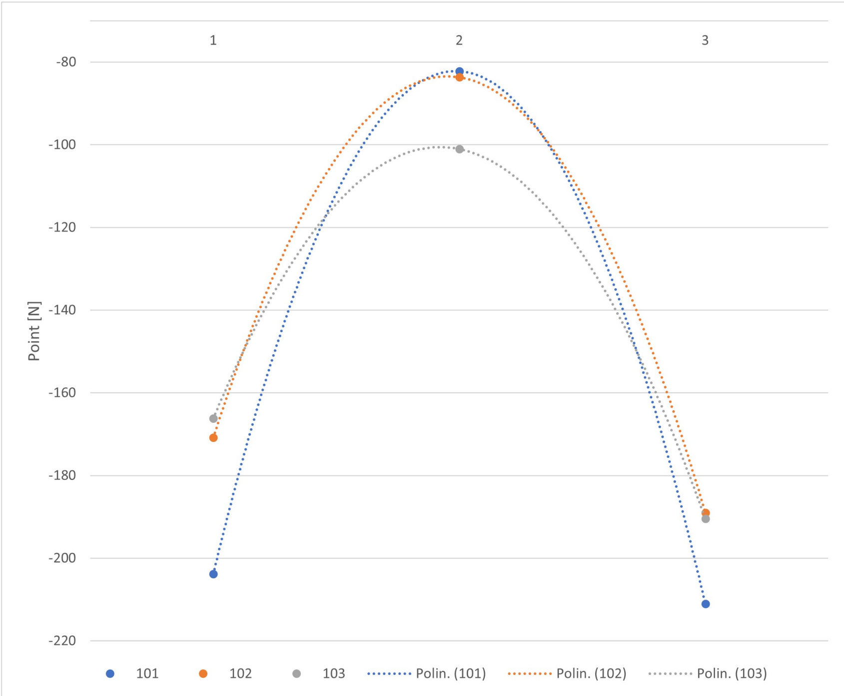

Figure 3.15: In blue the average second peak of the Ground Reaction Force with 101 force, in orange the average second peak of the Ground Reaction Force with 102 force, and in grey the average second peak of the Ground Reaction Force with 103 force.

As we would have liked, we obtained that the exercise with 101 level of force is higher than the other two, and the second peak for the exercise with 102 level of force is higher than the ones with 103 level of force.

From here, we calculated the standard deviation between the different curves with respect to the three points.

	o RED	x ORANGE	o ORANGE
101-102 [N]	38,95	30,55	53,11
101-103 [N]	43,68	33,61	52,04
102-103 [N]	29,35	28,12	42,67

Table 3.4: The first row considers the standard deviation between the three points with 101 and 102 force. The second row considers the standard deviation between the three points with 101 and 103 force. The third row considers the standard deviation between the three points with 102 and 103 force.

To have a final ideal, we obtain the average of the standard deviation for each of the points:

101-102 [N]	101-103 [N]	102-103 [N]
40,87	43,11	33,38

Table 3.5: The first row considers the standard deviation between the exercises with 101 and 102 force. The second row considers the standard deviation between the exercises with 101 and 103 force. The third row considers the standard deviation between the exercises with 102 and 103 force.

As we expected, the higher deviation is between the exercise with 101 force and the one with 103 force, since there is a higher difference in force.

3.1.3. Rotational Arm Position

In this section, we want to consider the evolution of the Rotation Arm Position and how it is different with respect to the three levels of force.

101 level force

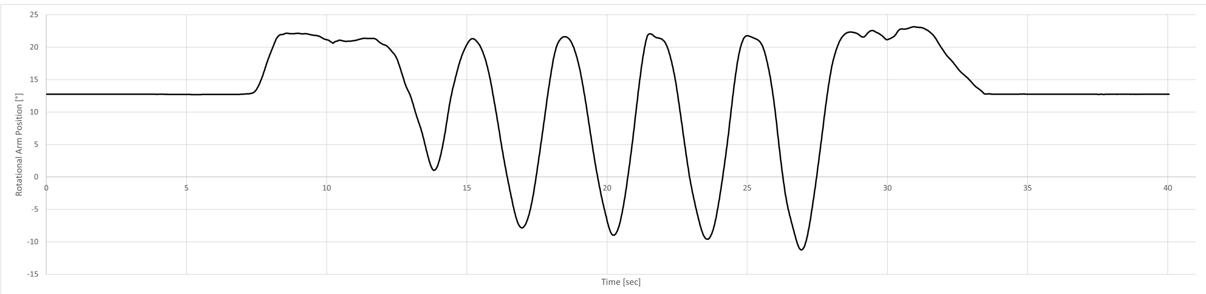

Figure 3.16: Rotational Arm Position evolution with the level of the force 101.

102 level force

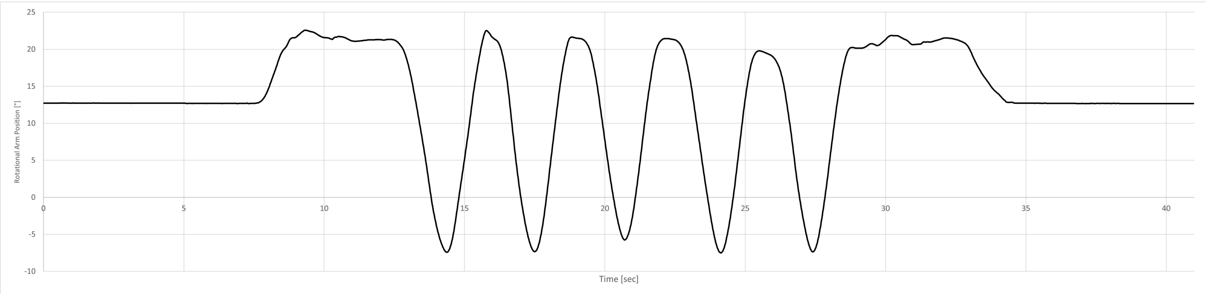

Figure 3.17: Rotational Arm Position evolution with the level of the force 102.

103 level force

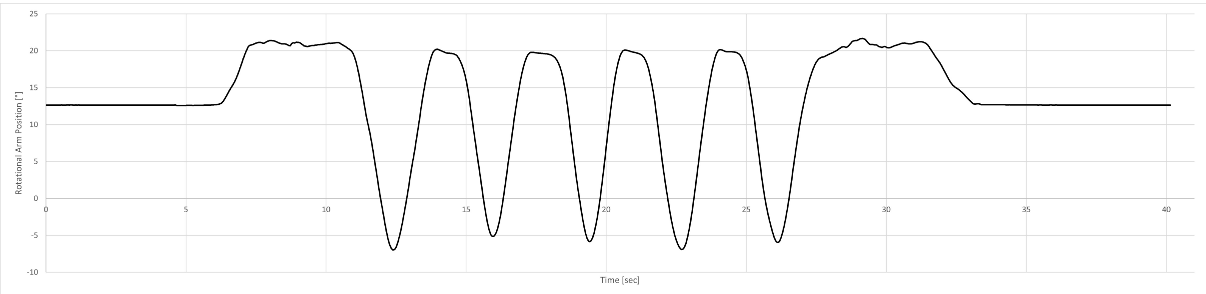

Figure 3.18: Rotational Arm Position evolution with the level of the force 103.

Explanation of the Rotational Arm Position

The evolutions of the Rotational Arm Position are similar to the ones for the Bar Height, this is why they depend on the flexions and extensions of the subject. As before, the maximum values for all three levels of force are very similar to each other for all the repetitions. It means that the subject returns at the same level at the end of the extension. Instead, the minimum values are not so constant between the three different exercises, and especially for the exercise with 101 force, these values are different concerning the different repetitions. It means that the subject doesn't have the same knee flexion for all the repetitions.

In the histogram, we can see in the same graphs the values of the maximum and minimum of the Rotational Arm Position for the three levels of force.

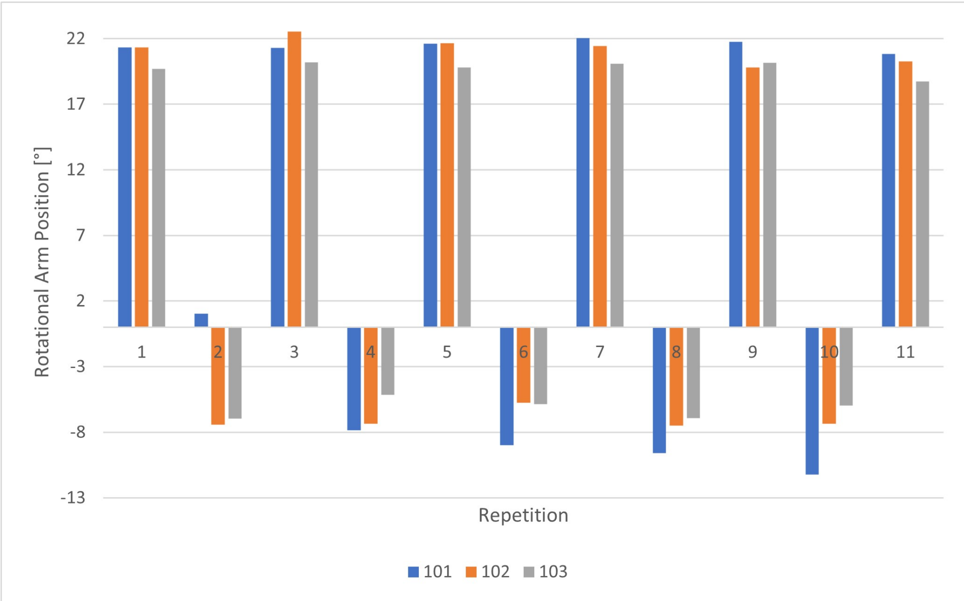

Figure 3.19: In blue the Rotational Arm Position values with 101 force, in orange the Rotational Arm Position values with 102 force, and in grey the Rotational Arm Position values with 103 force.

3.1.4. Bar Angle Position

In this section, we want to consider the evolution of the Bar Angle Position and how it is different with respect to the three levels of force.

101 level force

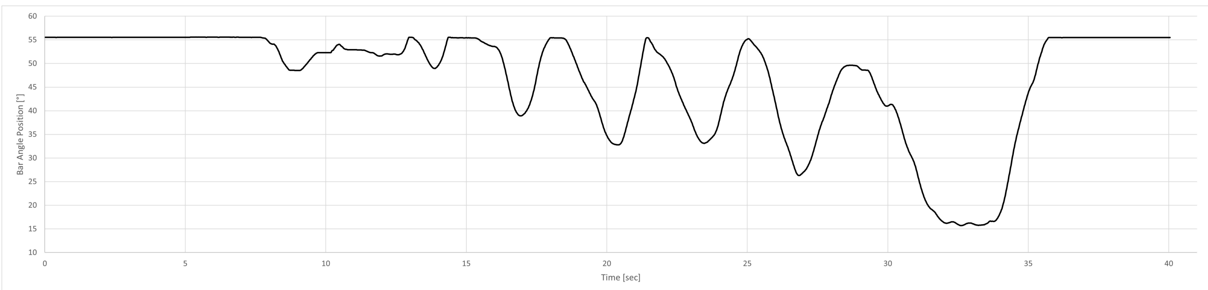

Figure 3.20: Bar Angle Position evolution with the level of the force 101.

102 level force

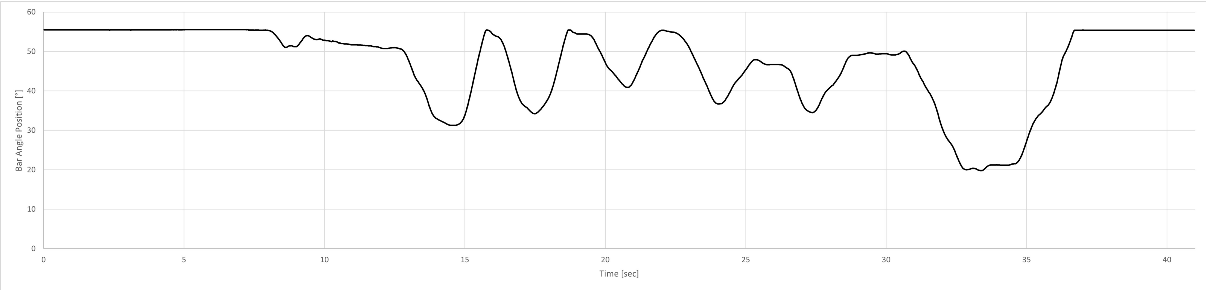

Figure 3.21: Bar Angle Position evolution with the level of the force 102.

103 level force

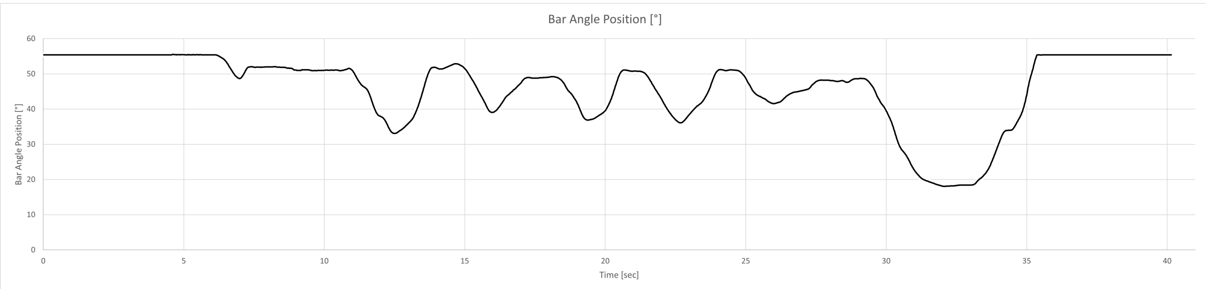

Figure 3.22: Bar Angle Position evolution with the level of the force 103.

Explanation of the Bar Angle Position

The evolutions of the Bar Angle Position are similar to the ones for the Bar Height, this is why they depend on the flexions and extensions of the subject. As before, the maximum values for all three levels of force are very similar to each other for all the repetitions. It means that the subject returns at the same level at the end of the extension. Instead, the minimum values are not so constant between the three different exercises, and especially for the exercise with 101 force, these values are different concerning the different repetitions. It means that the subject doesn't have the same knee flexion for all the repetitions.

In the histogram, we can see in the same graphs the values of the maximum and minimum of the Bar Angle Position for the three levels of force.

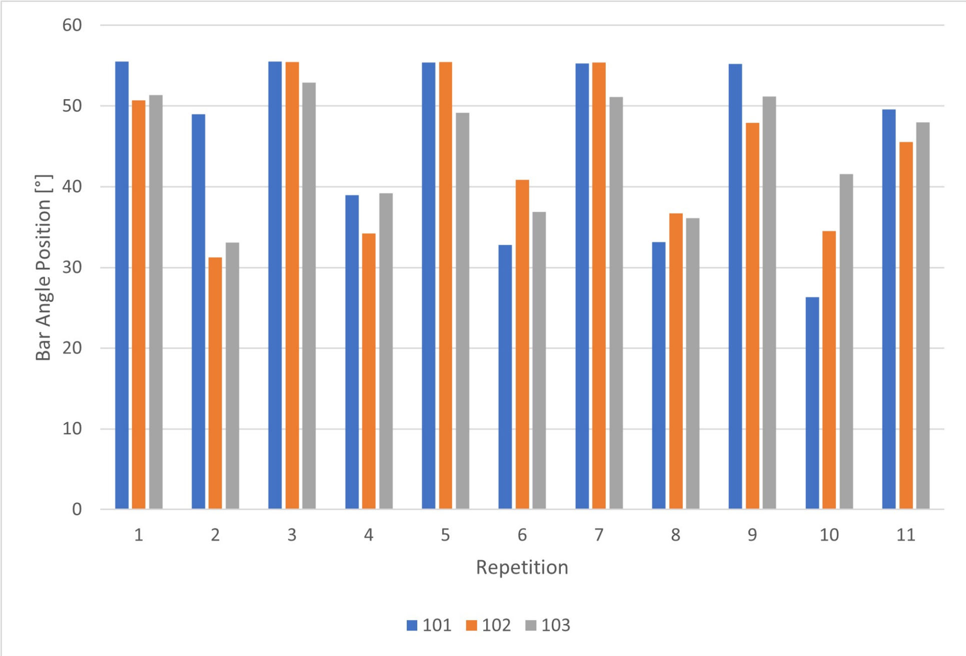

Figure 3.23: In blue the Bar Angle Position values with 101 force, in orange the Bar Angle Position values with 102 force, and in grey the Rotational Bar Angle values with 103 force.

3.2. Normal stance squat

3.2.1. Ground Reaction Force

We need to hand up a few steps in order to study the evolution of the Ground Reaction Force. The signal from the data was characterized by noise; for this, we implemented a code on Phyton to figure out a good signal where it was possible to identify four main points:

- X RED identifies the maximum value on the big peak
- X ORANGE identifies the maximum value on the small peak
- O RED identifies the minimum value before the X ORANGE point
- O ORANGE identifies the minimum value after the X ORANGE point

Since the Normal stance squat exercise was done for three different levels of force applied to the trapezius muscle, we are going to visualize the evolution of the Ground Reaction Force for each level.

101 level force

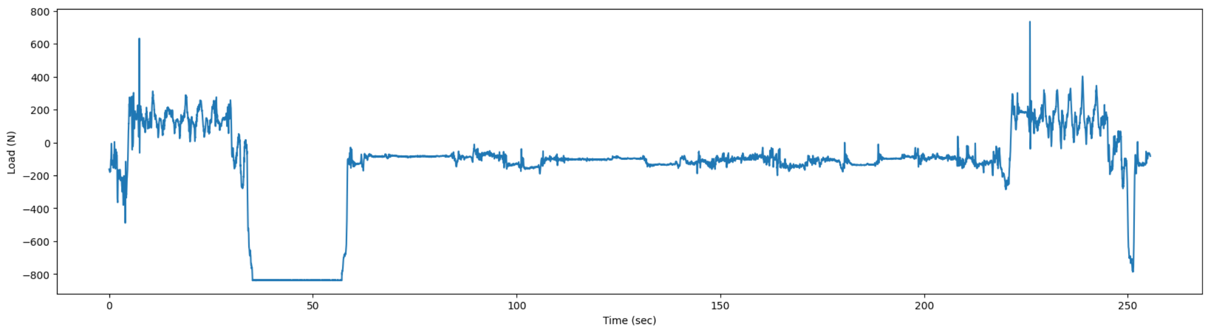

Figure 3.24: Ground Reaction Force original signal for Normal stance squat with 101 level of force.

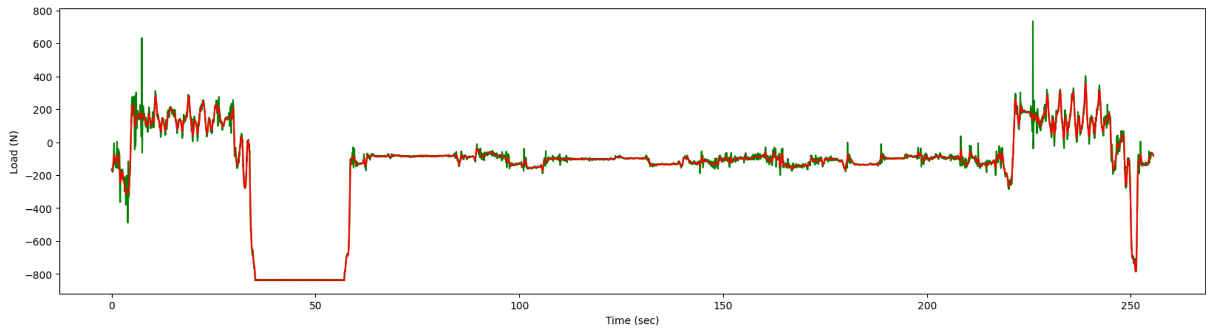

Figure 3.25: In green is the Ground Reaction Force original signal and in red is the Ground Reaction Force filtered signal.

From these two previous graphs, we could recognize that there was a mistake during the exercise, and the subject did it twice. For this reason, in the next graphs, we consider just the second exercise done.

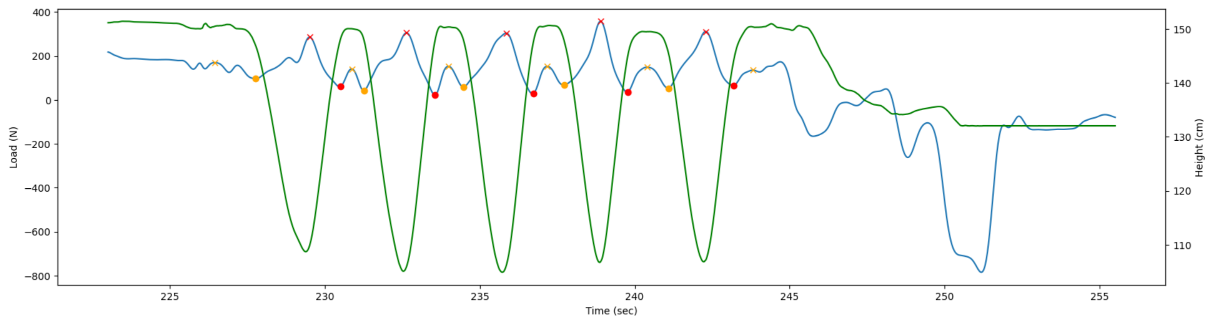

Figure 3.26: In blue the evolution of the load with 101 force, in green the evolution of the bar height with 101 force, x RED the maximum peaks, x ORANGE the second maximum peaks because of the contraction of the muscle, o RED the minimum peaks after the maximum peaks (x RED) and, o ORANGE the minimum peaks after the second maximum peaks (x ORANGE).

102 level force

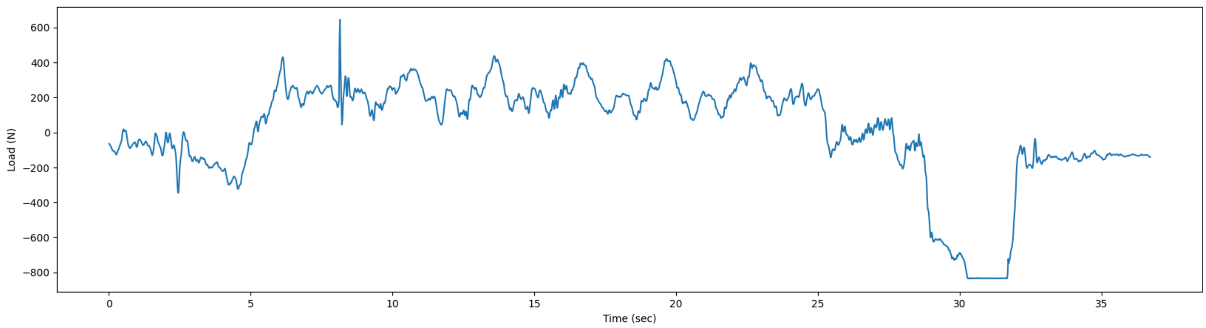

Figure 3.27: Ground Reaction Force original signal for Normal stance squat with 102 level of force.

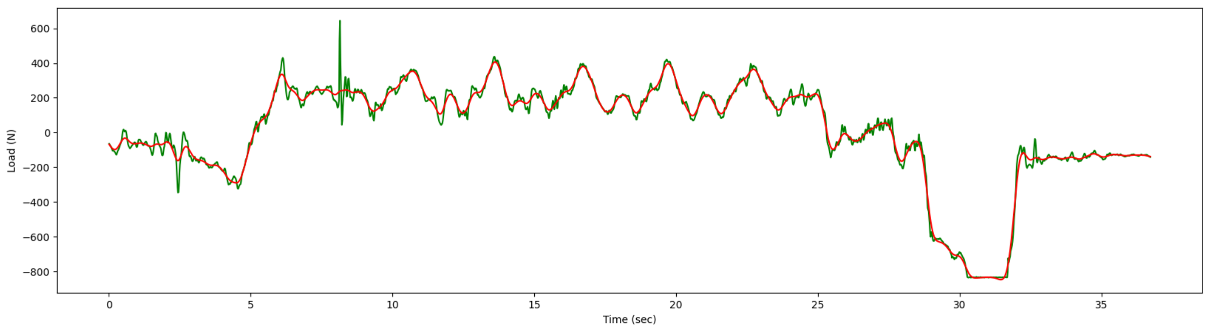

Figure 3.28: In green is the Ground Reaction Force original signal and in red is the Ground Reaction Force filtered signal.

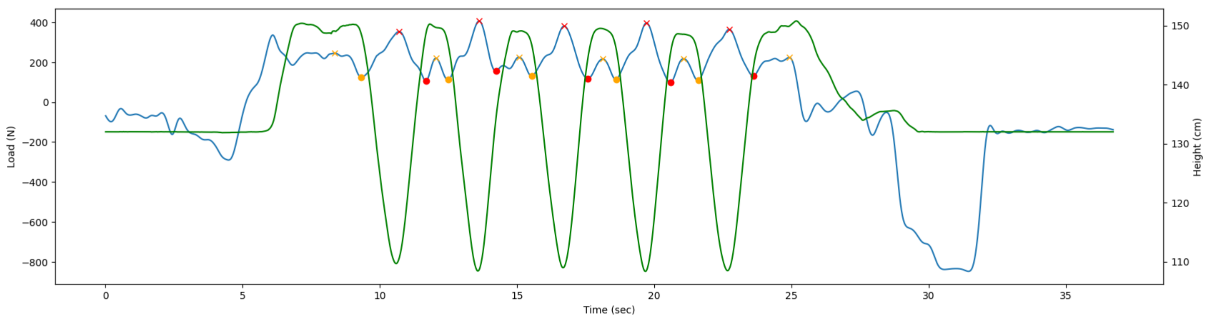

Figure 3.29: In blue the evolution of the load with 102 force, in green the evolution of the bar height with 102 force, x RED the maximum peaks, x ORANGE the second maximum peaks because of the contraction of the muscle, o RED the minimum peaks after the maximum peaks (x RED) and, o ORANGE the minimum peaks after the second maximum peaks (x ORANGE).

103 level force

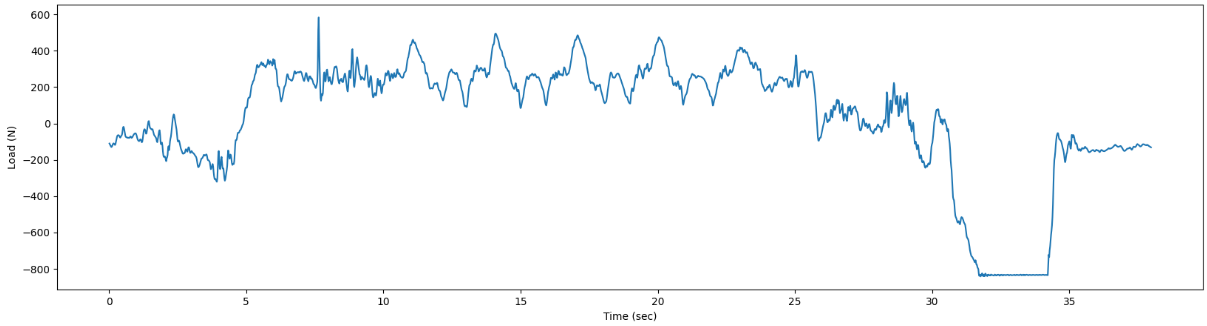

Figure 3.30: Ground Reaction Force original signal for Normal stance squat with 103 level of force.

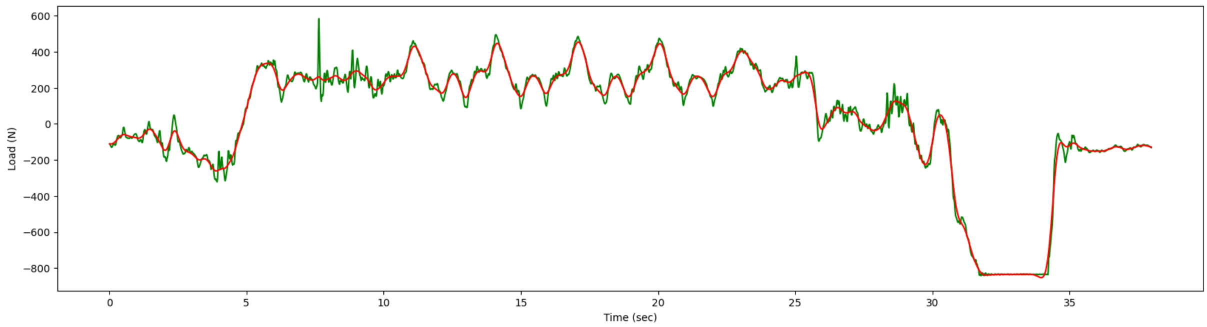

Figure 3.31: In green is the Ground Reaction Force original signal and in red is the Ground Reaction Force filtered signal.

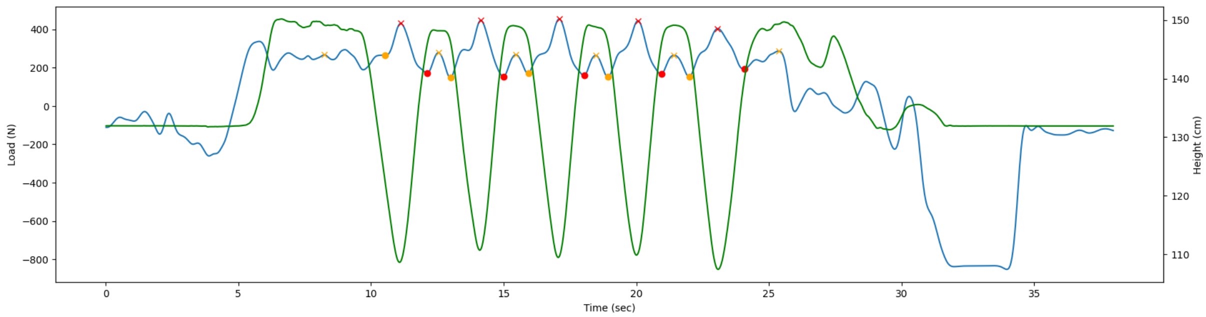

Figure 3.32: In blue the evolution of the load with 103 force, in green the evolution of the bar height with 103 force, x RED the maximum peaks, x ORANGE the second maximum peaks because of the contraction of the muscle, o RED the minimum peaks after the maximum peaks (x RED) and, o ORANGE the minimum peaks after the second maximum peaks (x ORANGE).

Explanation of the Ground Reaction Force

We want to focus our attention on the last graph for each level of force, see Figure 3.26, Figure 3.29 and Figure 3.32. The blue line is the evolution of the Ground Reaction Force, and in the same graph is also plotted the Bar Height signal to understand the timing of the exercise. The subject starts by standing up, where the Ground Reaction Force is low. While knee flexion exists, the Ground Reaction Force increases until a maximum point, identified in the graph as x RED. During the extension, the quadriceps and gluteal muscles work. During the flexion, the muscles acting are the hamstrings and adductors. Between the extension and flexion movement, we can consider a second peak (identified with the x ORANGE point, such as the minimum peak after the maximum peak (x RED)) due to the inertial force and co-contraction of the muscles (see Materials and Methods chapter). We are considering the Normal stance squat, where the small peaks (identified by the o RED, x ORANGE, and o ORANGE points) are at the end of the extension.

3.2.2. Bar Height

Since the Bar Height signal is already reported with the Ground Reaction Force evolution, see Figure 3.26, Figure 3.29 and Figure 3.32, in this section we want to focus on the maximum and minimum values of the Bar Height for the three level of forces.

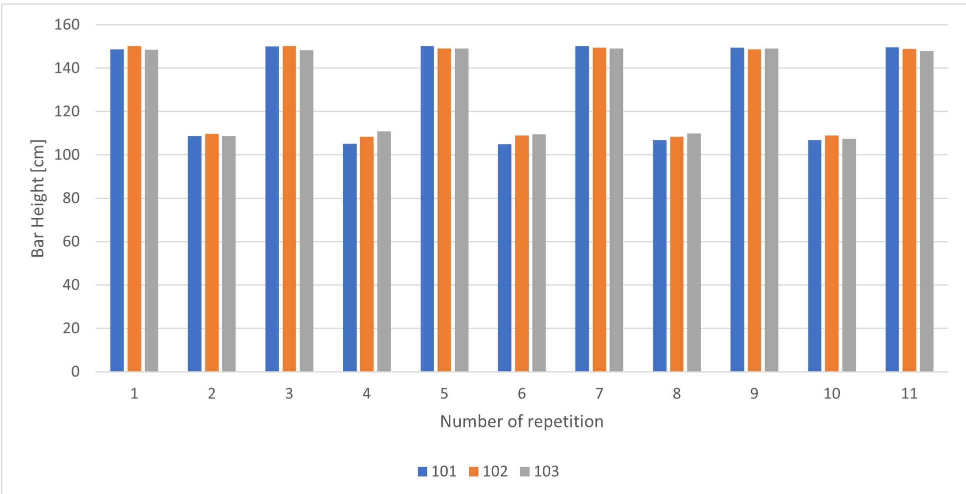

Figure 3.33: In blue the Bar Height values with 101 force, in orange the Bar Height values with 102 force, and in grey the Bar Height values with 103 force.

We can consider that the maximum values of the Bar Height for all three levels of force are very similar to each other for all the repetitions. It means that the subject returns at the same level at the end of the extension. Instead, the minimum values of the Bar Height present some differences with respect to the different repetitions. In general, the exercise with 101 force has lower minimum values, then there is the exercise with 102 force, and as highest the exercise with 103 force. In any case, repetition by repetition is better to check the different behavior.

Relationship between Ground Reaction Force and Bar Height

One of the main aims of the thesis is to study how the two peaks that characterized the Ground Reaction Force behave, changing along the different type of exercise and level of force.

First of all, we focus on the second peak, the small one designed by o RED, x ORANGE, and o ORANGE points. As already described in the Materials and Methods section, the presence of the second peaks is due to inertial force and the co-contraction of the muscles because the subject changes movement. In the Normal stance squat, the second peak is while changing movement from extension to flexion at the level of the maximum values of the Bar Height. We visualized a strong relationship between the values of the second peaks with the values of the Bar Height. We thought that, in general, with a higher force, the second peaks should be higher than the ones with an lower force. So, we could expect that the second peak for the exercise with 103 level of force should be higher than the other two, and the second peak for the exercise with 102 level of force should be higher than the ones with 101 level of force.

However, if we plot the second peaks repetition by repetition, we can see that this assumption was correct. Here we reported the graphs:

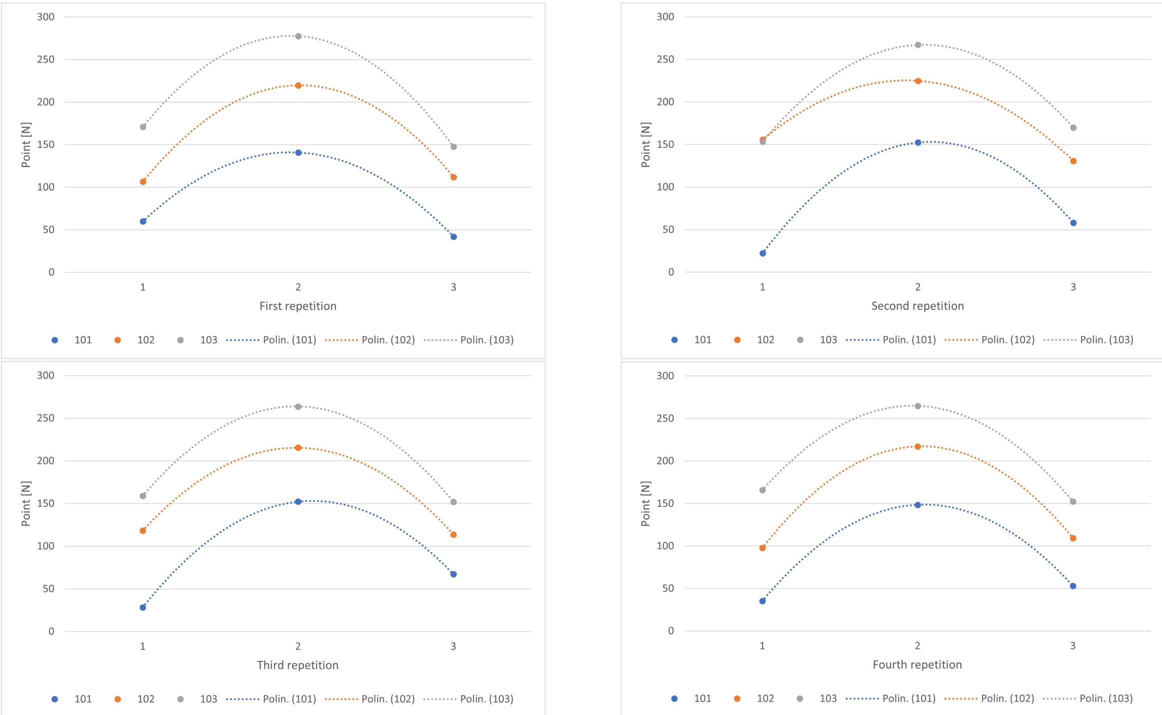

Figure 3.34: Considering each repetition, in blue the second peak of the Ground Reaction Force with 101 force, in orange the second peak of the Ground Reaction Force with 102 force, and in grey the second peak of the Ground Reaction Force with 103 force.

Even if the behavior of the second peaks for the Single leg squat was not the same for all the repetitions because of the different flexions made by the subject, for the Normal stance squat the behavior of the second peaks is the same for all the repetitions. As we can see in Figure 3.33, the subject reaches very few different levels of the flexions for the different repetitions. Thanks to this quite constant behavior the second peaks are coherent for each repetition.

As explained in the Materials and Methods section, if a person performs a squat with a quick and explosive movement, the quadriceps muscles may contract rapidly and generate a secondary peak in the force curve. Alternatively, if a person performs a squat with a slower and more controlled movement, the hamstrings and gluteal muscles may contract more gradually, resulting in a smoother and more gradual decrease in the Ground Reaction Force.

To study this behavior, we calculate the difference between the maximum point (x RED) and the second maximum point (x ORANGE) identified in the Ground Reaction Force. In the graph below, we want to do a comparison of this difference with respect to the three levels of force used for the exercise.

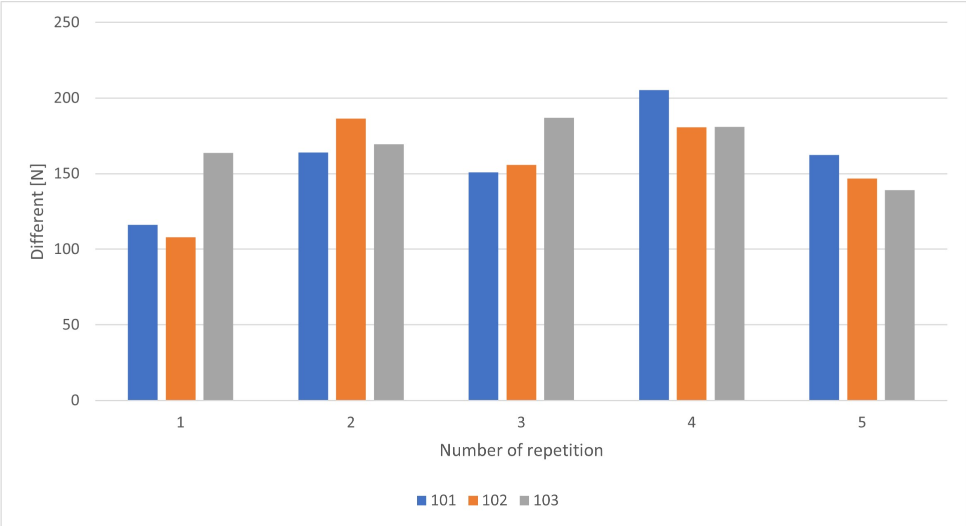

Figure 3.35: In blue the difference between x RED and x ORANGE with 101 force, in orange the difference between x RED and x ORANGE with 102 force, and in grey the difference between x RED and x ORANGE with 103 force.

The higher the distance, the lower the x ORANGE point, which means that the second peaks are lower. From this result, we can say that the distances are in general higher for the 103 level of force because the squat is more quick and explosive, having a higher force. Instead, the distances are in general lower for the 101 level of force because the squat is slower and more controlled due to the lower force. But we can not say the same for the two last repetitions.

Another important parameter to take into consideration is the height in terms of the Ground Reaction Force of the first peak, indicated by the x RED point. There is this peak at the end of the flexion, and as we could expect, the exercise with 103 level of force has higher values of x RED points because there is more weight. As we saw in Figure 3.33, the level of the extension doesn't change with respect to the level of force, it means that the x RED values don't depend on the Bar Height. Here are reported the x RED evolution:

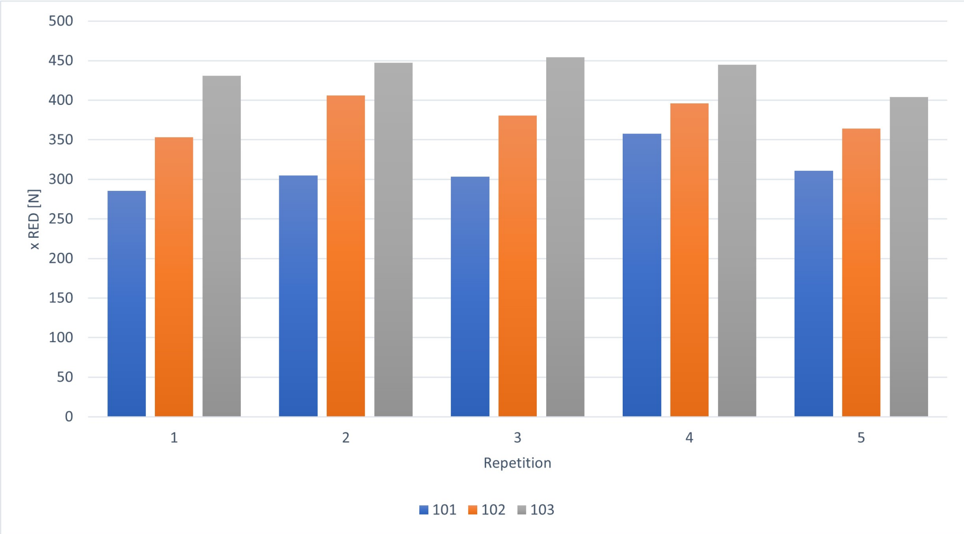

Figure 3.36: In blue the x RED peak with 101 force, in orange the x RED peak with 102 force, and in grey the x RED peak with 103 force.

Deviation of the second peaks concerning the level of the force

In order to obtain a statistical behavior of the second peaks in the Ground Reaction Force, we calculated the average of the points that identified the curve and obtained the standard deviation between the three levels of force. With this approach, we can evaluate how the Ground Reaction Force changes facing the same exercise but having different forces at the level of the trapezius muscle.

In the tables below, we reported the averages and the standard deviation of the three points that define the second peaks depending on the level of force.

	o RED	x ORANGE	o ORANGE
101 force [N]	36,44±16,53	148,47±5,45	55,01±10,52
102 force [N]	119,68±25,62	219,33±4,14	116,47±9,69
103 force [N]	162,27±7,63	268,35±6,31	155,43±9,84

Table 3.6: Considering the three levels of the force, the table reports the average (first number) and the standard deviation (second number) of the three points that define the second peaks.

To visualize better the evolution of the point values that identify the second peak, we plotted the following graph:

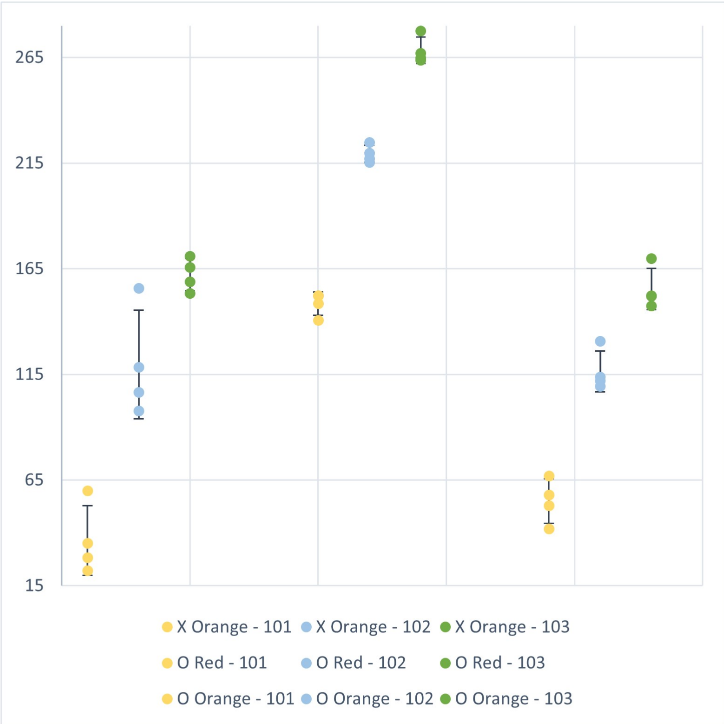

Figure 3.37: The graph reports in yellow the points obtained from the exercise with 101 level of force, in blue the points from the 102 level of force and in green the points from the 103 level of force. The first column represents the O RED points, the second column represents the X ORANGE points and the third column represents the O ORANGE points. The black lines indicate the standard deviation of each point from their average.

Using the average values, we plotted the average second peaks for the Normal stance squat:

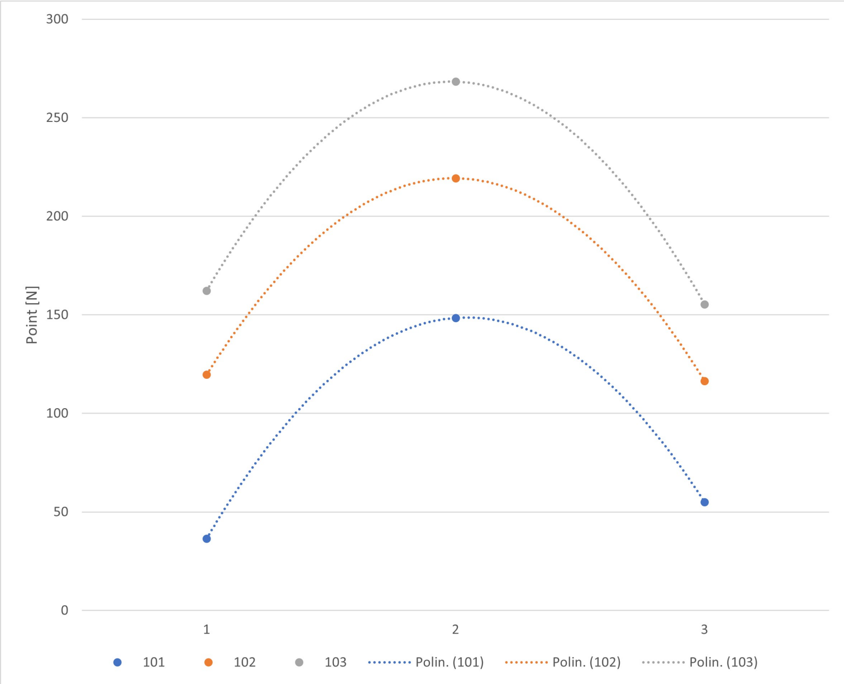

Figure 3.38: In blue the average second peak of the Ground Reaction Force with 101 force, in orange the average second peak of the Ground Reaction Force with 102 force, and in grey the average second peak of the Ground Reaction Force with 103 force.

As we would have liked, we obtained that the exercise with 101 level of force is higher than the other two, and the second peak for the exercise with 102 level of force is higher than the ones with 103 level of force.

From here, we calculated the standard deviation between the different curves with respect to the three points.

	o RED	x ORANGE	o ORANGE
101-102 [N]	48,76	38,14	34,16
101-103 [N]	68,31	64,31	54,50
102-103 [N]	28,72	26,66	22,70

Table 3.7: The first row considers the standard deviation between the three points with 101 and 102 force. The second row considers the standard deviation between the three points with 101 and 103 force. The third row considers the standard deviation between the three points with 102 and 103 force.

To have a final ideal, we obtain the average of the standard deviation for each of the points:

101-102 [N]	101-103 [N]	102-103 [N]
40,36	62,37	26,03

Table 3.8: The first row considers the standard deviation between the exercises with 101 and 102 force. The second row considers the standard deviation between the exercises with 101 and 103 force. The third row considers the standard deviation between the exercises with 102 and 103 force.

As we expected, the higher deviation is between the exercise with 101 force and the one with 103 force, since there is a higher difference in force.

3.2.3. Rotational Arm Position

In this section, we want to consider the evolution of the Rotation Arm Position and how it is different with respect to the three levels of force.

101 level force

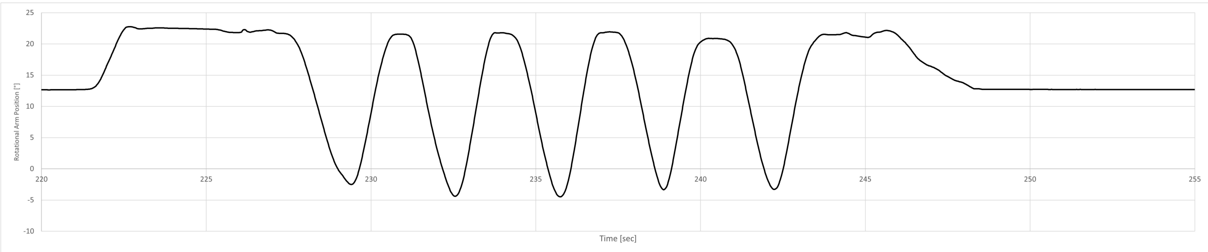

Figure 3.39: Rotational Arm Position evolution with the level of the force 101.

102 level force

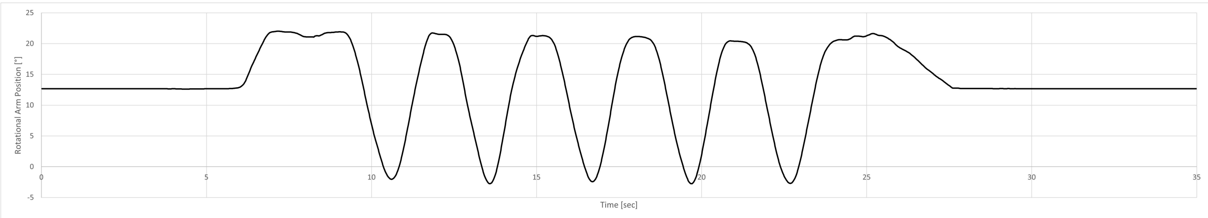

Figure 3.40: Rotational Arm Position evolution with the level of the force 102.

103 level force

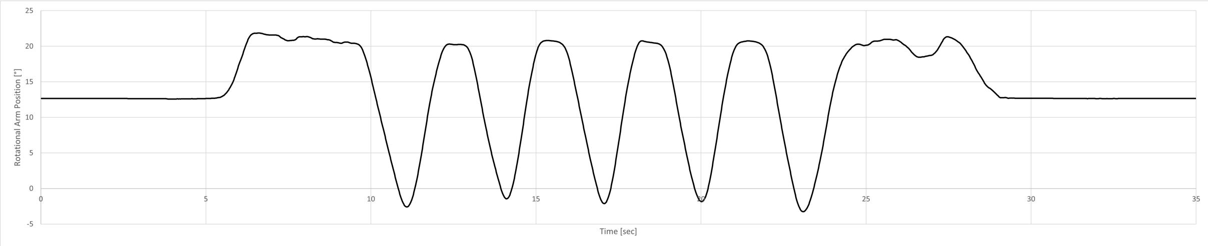

Figure 3.41: Rotational Arm Position evolution with the level of the force 103.

Explanation of the Rotational Arm Position

The evolutions of the Rotational Arm Position are similar to the ones for the Bar Height, this is why they depend on the flexions and extensions of the subject. As before, the maximum values for all three levels of force are very similar to each other for all the repetitions. It means that the subject returns at the same level at the end of the extension. Instead, the minimum values are less constant between the three different exercises. It means that the subject doesn't have the same knee flexion for all the repetitions.

In the histogram, we can see in the same graphs the values of the maximum and minimum of the Rotational Arm Position for the three levels of force.

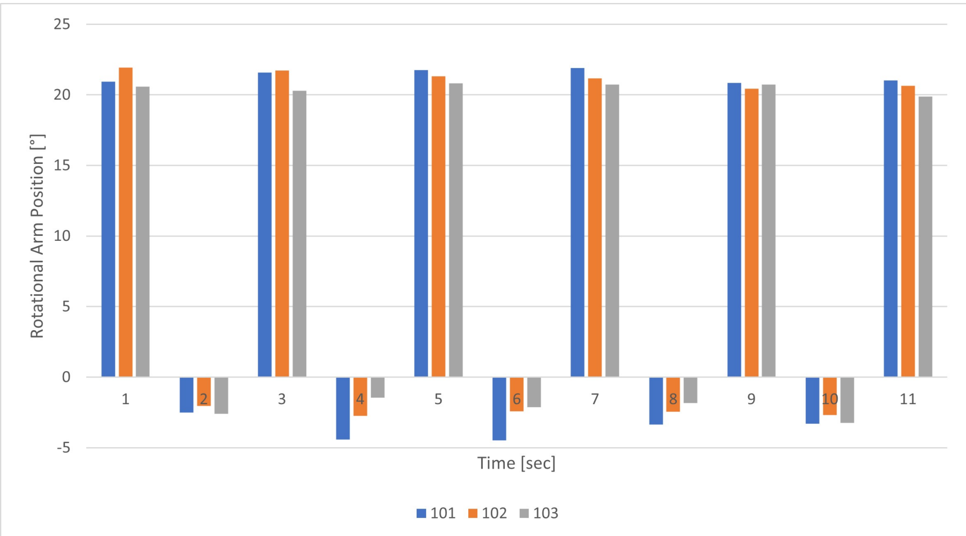

Figure 3.42: In blue the Rotational Arm Position values with 101 force, in orange the Rotational Arm Position values with 102 force, and in grey the Rotational Arm Position values with 103 force.

3.2.4. Bar Angle Position

In this section, we want to consider the evolution of the Bar Angle Position and how it is different with respect to the three levels of force.

101 level force

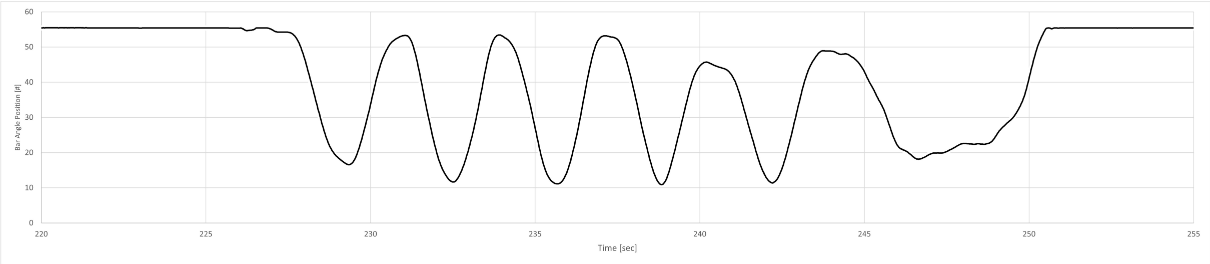

Figure 3.43: Bar Angle Position evolution with the level of the force 101.

102 level force

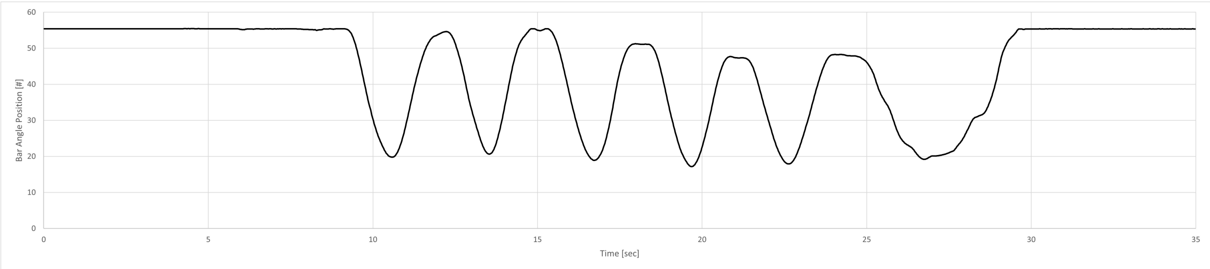

Figure 3.44: Bar Angle Position evolution with the level of the force 102.

103 level force

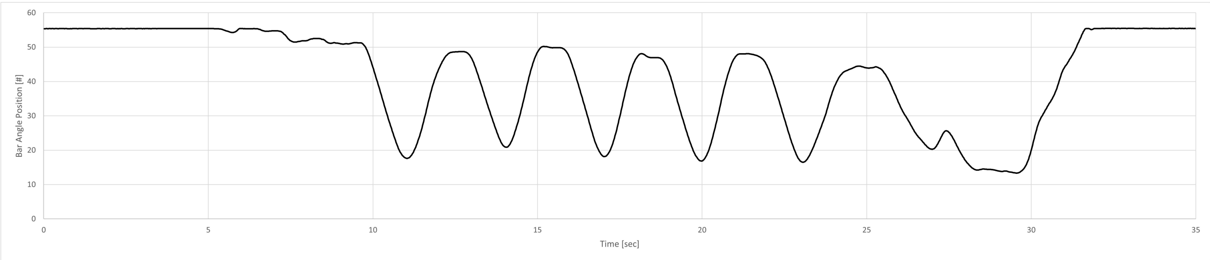

Figure 3.45: Bar Angle Position evolution with the level of the force 103.

Explanation of the Bar Angle Position

The evolutions of the Bar Angle Position are similar to the ones for the Bar Height, this is why they depend on the flexions and extensions of the subject. As before, the maximum values for all three levels of force are very similar to each other for all the repetitions. It means that the subject returns at the same level at the end of the extension. Instead, the minimum values are less constant between the three different exercises. It means that the subject doesn't have the same knee flexion for all the repetitions.

In the histogram, we can see in the same graphs the values of the maximum and minimum of the Bar Angle Position for the three levels of force.

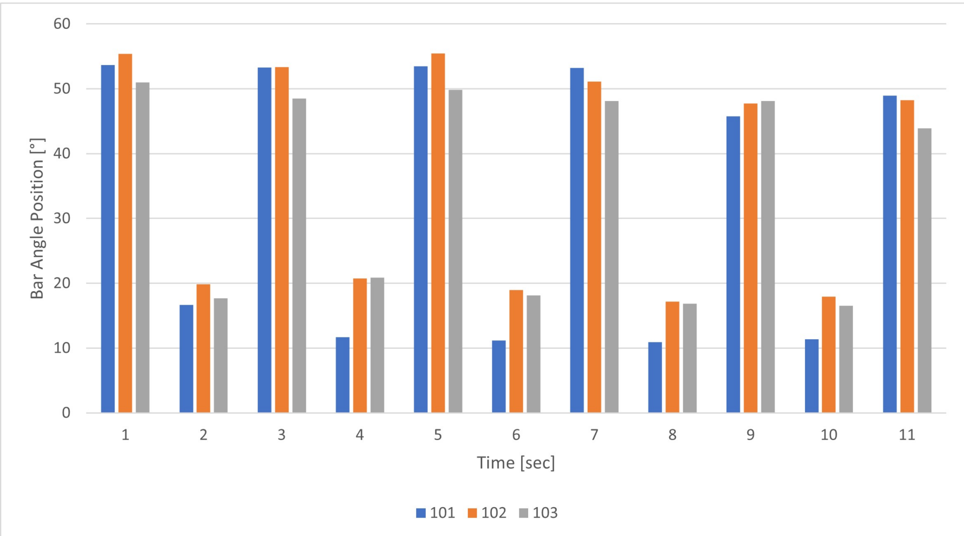

Figure 3.46: In blue the Bar Angle Position values with 101 force, in orange the Bar Angle Position values with 102 force, and in grey the Rotational Bar Angle values with 103 force.

3.3. Wide stance squat

3.3.1. Ground Reaction Force

We need to hand up a few steps in order to study the evolution of the Ground Reaction Force. The signal from the data was characterized by noise; for this, we implemented a code on Phyton to figure out a good signal where it was possible to identify four main points:

- X RED identifies the maximum value on the big peak
- X ORANGE identifies the maximum value on the small peak
- O RED identifies the minimum value before the X ORANGE point
- O ORANGE identifies the minimum value after the X ORANGE point

Since the Wide stance squat exercise was done for three different levels of force applied to the trapezius muscle, we are going to visualize the evolution of the Ground Reaction Force for each level.

101 level force

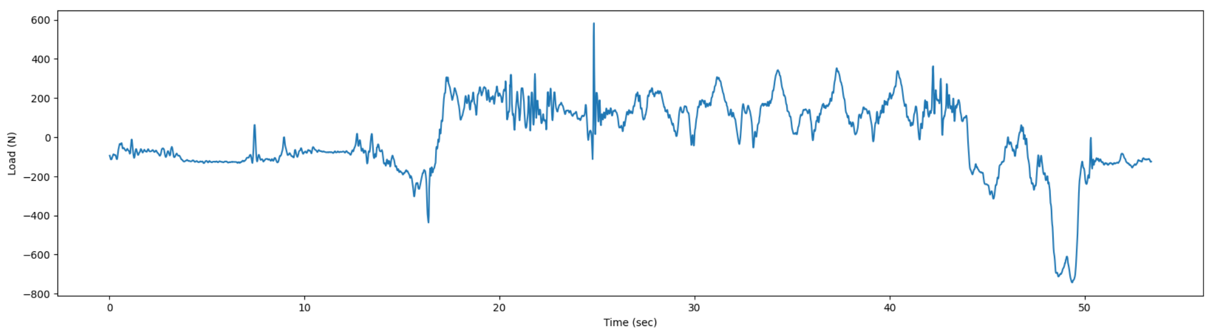

Figure 3.47: Ground Reaction Force original signal for Normal stance squat with 101 level of force.

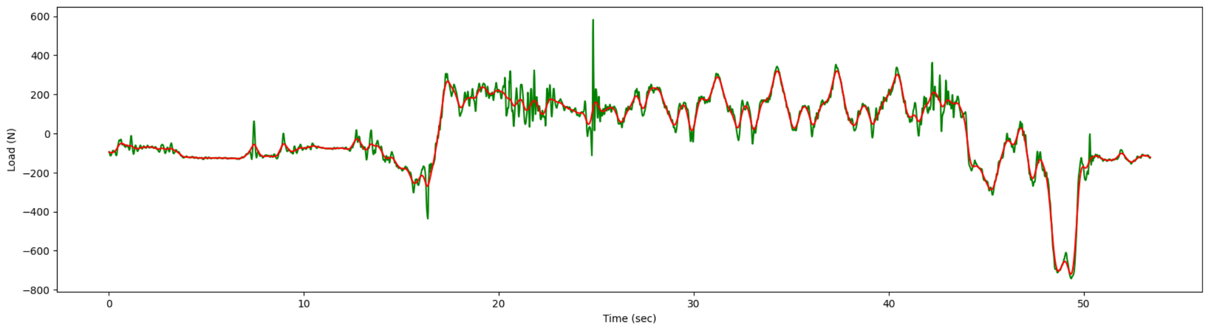

Figure 3.48: In green is the Ground Reaction Force original signal and in red is the Ground Reaction Force filtered signal.

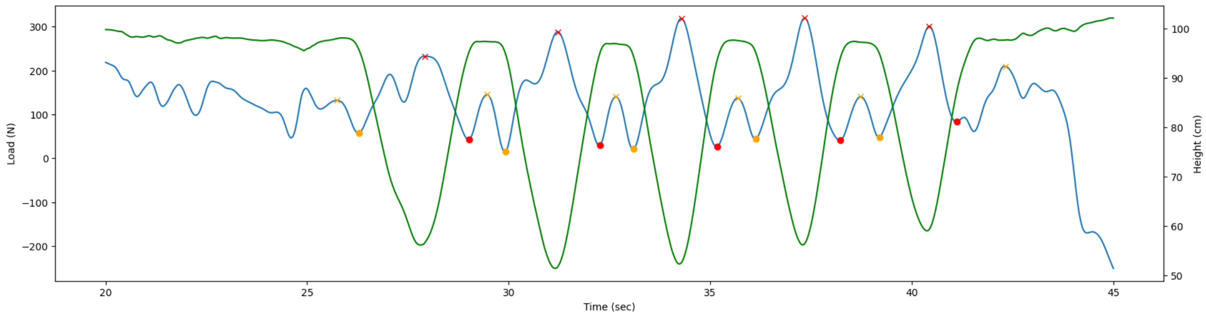

Figure 3.49: In blue the evolution of the load with 101 force, in green the evolution of the bar height with 101 force, x RED the maximum peaks, x ORANGE the second maximum peaks because of the contraction of the muscle, o RED the minimum peaks after the maximum peaks (x RED) and, o ORANGE the minimum peaks after the second maximum peaks (x ORANGE).

102 level force

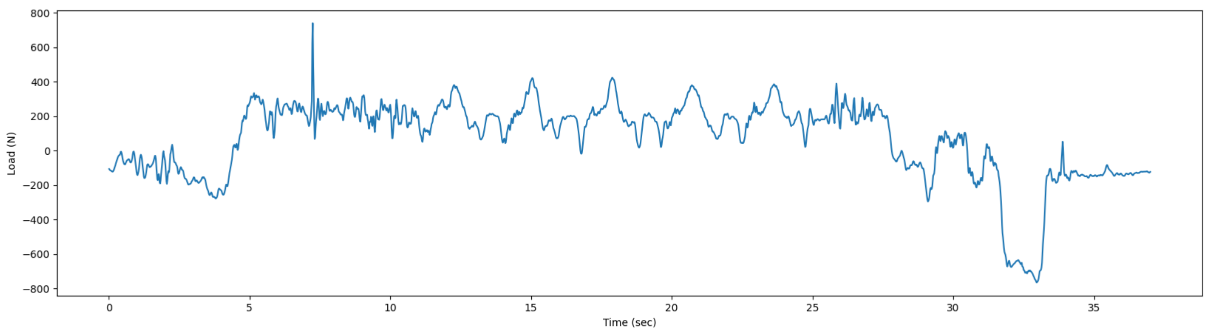

Figure 3.50: Ground Reaction Force original signal for Normal stance squat with 102 level of force.

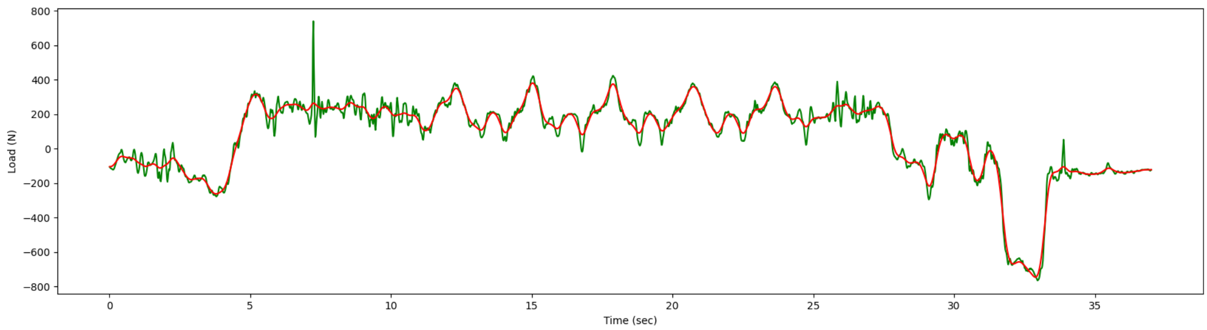

Figure 3.51: In green is the Ground Reaction Force original signal and in red is the Ground Reaction Force filtered signal.

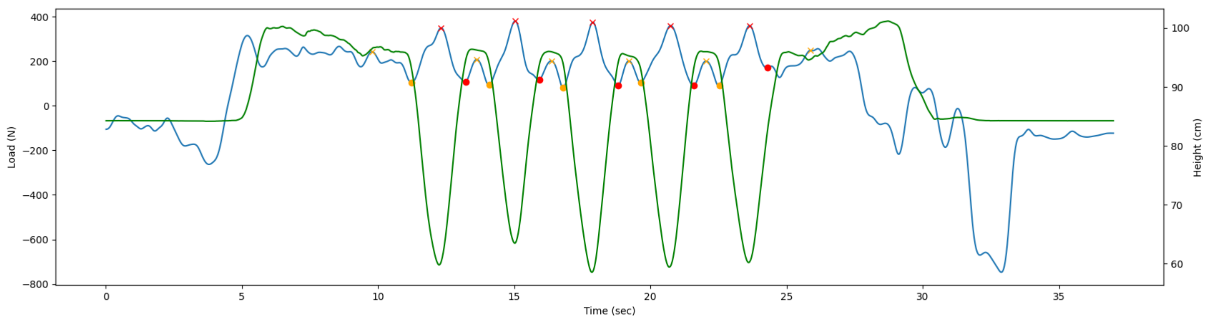

Figure 3.52: In blue the evolution of the load with 102 force, in green the evolution of the bar height with 102 force, x RED the maximum peaks, x ORANGE the second maximum peaks because of the contraction of the muscle, o RED the minimum peaks after the maximum peaks (x RED) and, o ORANGE the minimum peaks after the second maximum peaks (x ORANGE).

103 level force

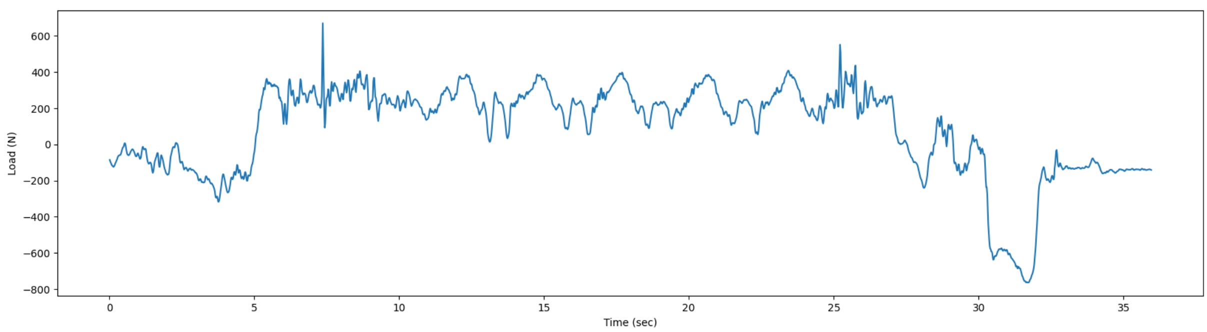

Figure 3.53: Ground Reaction Force original signal for Normal stance squat with 103 level of force.

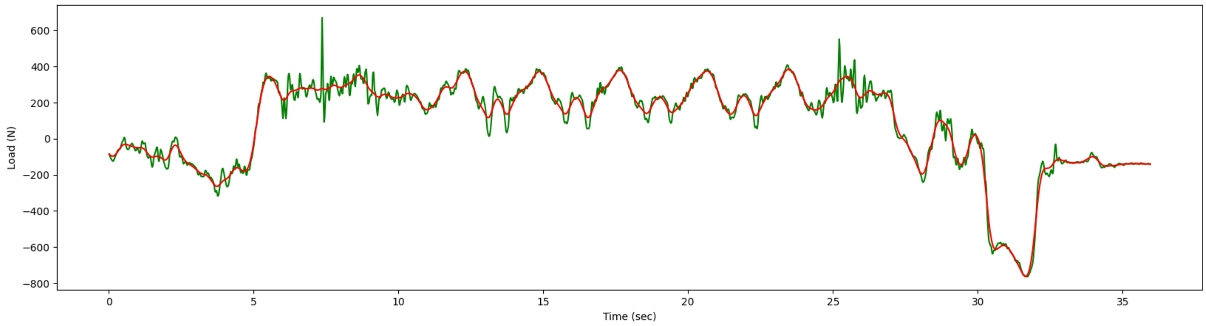

Figure 3.54: In green is the Ground Reaction Force original signal and in red is the Ground Reaction Force filtered signal.

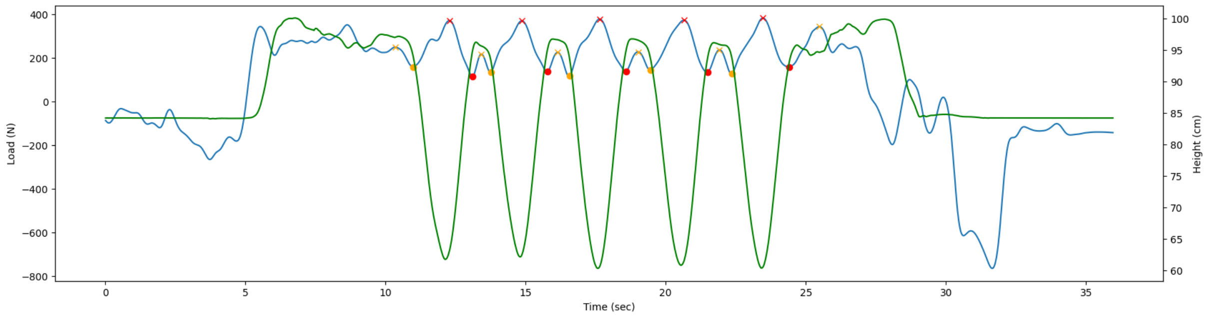

Figure 3.55: In blue the evolution of the load with 103 force, in green the evolution of the bar height with 103 force, x RED the maximum peaks, x ORANGE the second maximum peaks because of the contraction of the muscle, o RED the minimum peaks after the maximum peaks (x RED) and, o ORANGE the minimum peaks after the second maximum peaks (x ORANGE).

Explanation of the Ground Reaction Force

We want to focus our attention on the last graph for each level of force, see Figure 3.49, Figure 3.52 and Figure 3.55. The blue line is the evolution of the Ground Reaction Force, and in the same graph is also plotted the Bar Height signal to understand the timing of the exercise. The subject starts by standing up, where the Ground Reaction Force is low. While knee flexion exists, the Ground Reaction Force increases until a maximum point, identified in the graph as x RED. During the extension, the quadriceps and gluteal muscles work. During the flexion, the muscles acting are the hamstrings and adductors. Between the flexion and extension movement, we can consider a second peak (identified with the x ORANGE point, such as the minimum peak after the maximum peak (x RED)) due to the inertial force and co-contraction of the muscles (see Materials and Methods chapter). We are considering the Wide stance squat, where the small peaks (identified by the o RED, x ORANGE, and o ORANGE points) are at the end of the extension.

3.3.2. Bar Height

Since the Bar Height signal is already reported with the Ground Reaction Force evolution, see Figure 3.49, Figure 3.52 and Figure 3.55, in this section we want to focus on the maximum and minimum values of the Bar Height for the three level of forces.

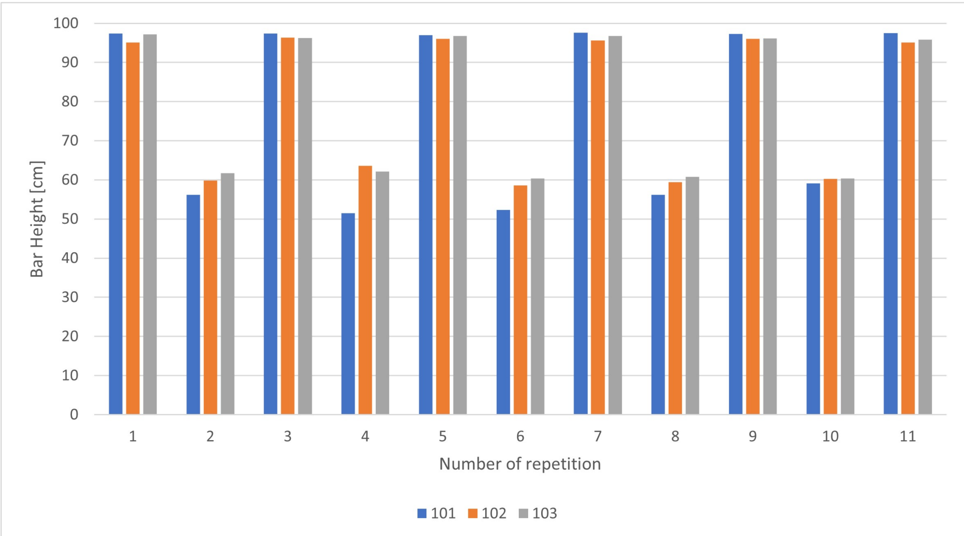

Figure 3.56: In blue the Bar Height values with 101 force, in orange the Bar Height values with 102 force, and in grey the Bar Height values with 103 force.

We can consider that the maximum values of the Bar Height for all three levels of force are very similar to each other for all the repetitions. It means that the subject returns at the same level at the end of the extension. Instead, the minimum values of the Bar Height present some differences with respect to the different repetitions. In general, the exercise with 101 force has lower minimum values, then there is the exercise with 102 force, and as highest the exercise with 103 force. In any case, repetition by repetition is better to check the different behavior.

Relationship between Ground Reaction Force and Bar Height

One of the main aims of the thesis is to study how the two peaks that characterized the Ground Reaction Force behave, changing along the different type of exercise and level of force.

First of all, we focus on the second peak, the small one designed by o RED, x ORANGE, and o ORANGE points. As already described in the Materials and Methods section, the presence of the second peaks is due to inertial force and the co-contraction of the muscles because the subject changes movement. In the Wide stance squat, the second peak is while changing movement from extension to flexion at the level of the maximum values of the Bar Height. We visualized a strong relationship between the values of the second peaks with the values of the Bar Height. We thought that, in general, with a higher force, the second peaks should be higher than the ones with an lower force. So, we could expect that the second peak for the exercise with 103 level of force should be higher than the other two, and the second peak for the exercise with 102 level of force should be higher than the ones with 101 level of force.

However, if we plot the second peaks repetition by repetition, we can see that this assumption was correct. Here we reported the graphs:

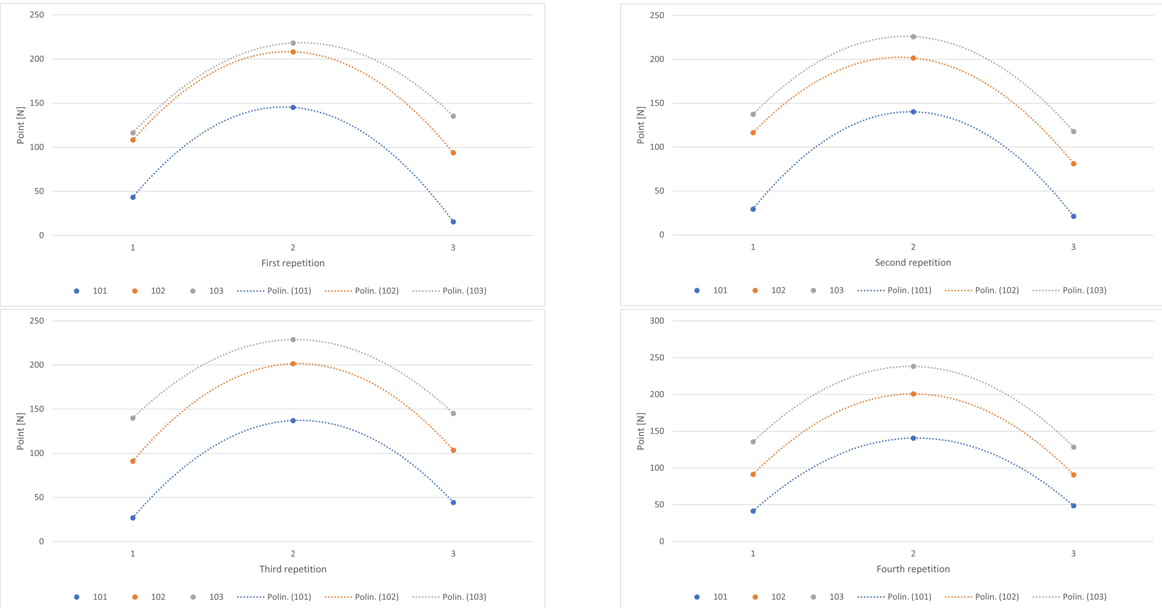

Figure 3.57: Considering each repetition, in blue the second peak of the Ground Reaction Force with 101 force, in orange the second peak of the Ground Reaction Force with 102 force, and in grey the second peak of the Ground Reaction Force with 103 force.

Even if the behavior of the second peaks for the Single leg squat was not the same for all the repetitions because of the different flexions made by the subject, for the Wide stance squat the behavior of the second peaks is the same for all the repetitions. As we can see in Figure 3.56, the subject reaches very few different levels of the flexions for the different repetitions. Thanks to this quite constant behavior, the second peaks are coherent for each repetition.

As explained in the Materials and Methods section, if a person performs a squat with a quick and explosive movement, the quadriceps muscles may contract rapidly and generate a secondary peak in the force curve. Alternatively, if a person performs a squat with a slower and more controlled movement, the hamstrings and gluteal muscles may contract more gradually, resulting in a smoother and more gradual decrease in the Ground Reaction Force.

To study this behavior, we calculate the difference between the maximum point (x RED) and the second maximum point (x ORANGE) identified in the Ground Reaction Force. In the graph below, we want to do a comparison of this difference with respect to the three levels of force used for the exercise.

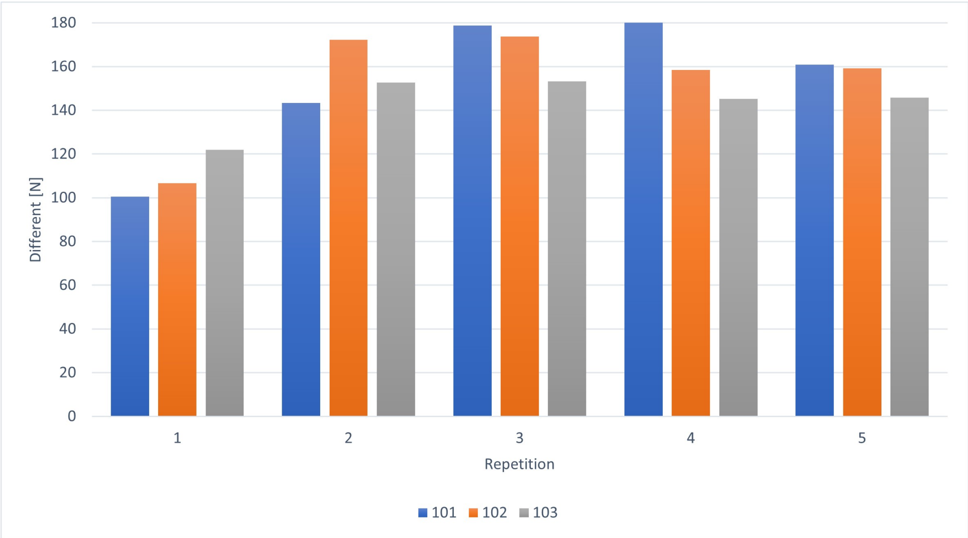

Figure 3.58: In blue the difference between x RED and x ORANGE with 101 force, in orange the difference between x RED and x ORANGE with 102 force, and in grey the difference between x RED and x ORANGE with 103 force.

The higher the distance, the lower the x ORANGE point, which means that the second peaks are lower. From this result, we can say that the distances are in general higher for the 101 level of force because the squat is more quick and explosive. Instead, from the previous exercises, we obtained higher differences for the 103 level of force. In this case, the distances are in general lower for the 103 level of force because the squat is slower and more controlled. In any case, repetition by repetition is better to check the different behavior.

Another important parameter to take into consideration is the height in terms of the Ground Reaction Force of the first peak, indicated by the x RED point. There is this peak at the end of the flexion, and as we could expect, the exercise with 103 level of force has higher values of x RED points because there is more weight. As we saw in Figure 3.56, the level of the extension doesn't change with respect to the level of force, it means that the x RED values don't depend on the Bar Height. Here are reported the x RED evolution:

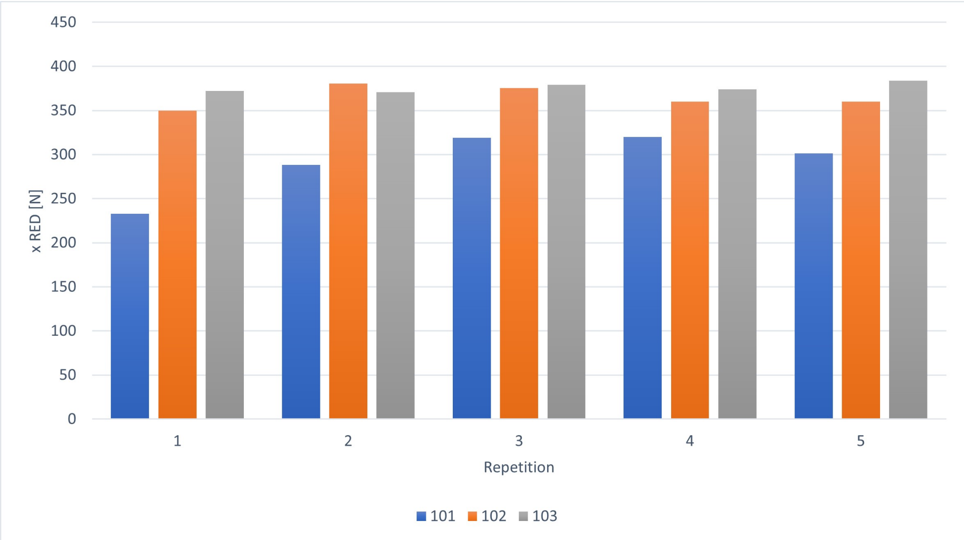

Figure 3.59: In blue the x RED peak with 101 force, in orange the x RED peak with 102 force, and in grey the x RED peak with 103 force.

Deviation of the second peaks concerning the level of the force

In order to obtain a statistical behavior of the second peaks in the Ground Reaction Force, we calculated the average of the points that identified the curve and obtained the standard deviation between the three levels of force. With this approach, we can evaluate how the Ground Reaction Force changes facing the same exercise but having different forces at the level of the trapezius muscle.

In the tables below, we reported the averages and the standard deviation of the three points that define the second peaks depending on the level of force.

	o RED	x ORANGE	o ORANGE
101 force [N]	35,25±8,25	140,79±3,29	32,40±16,39
102 force [N]	101,80±12,72	203,00±3,49	92,32±9,27
103 force [N]	132,29±10,81	227,76±8,23	131,72±11,52

Table 3.9: Considering the three levels of the force, the table reports the average (first number) and the standard deviation (second number) of the three points that define the second peaks.

To visualize better the evolution of the point values that identify the second peak, we plotted the following graph:

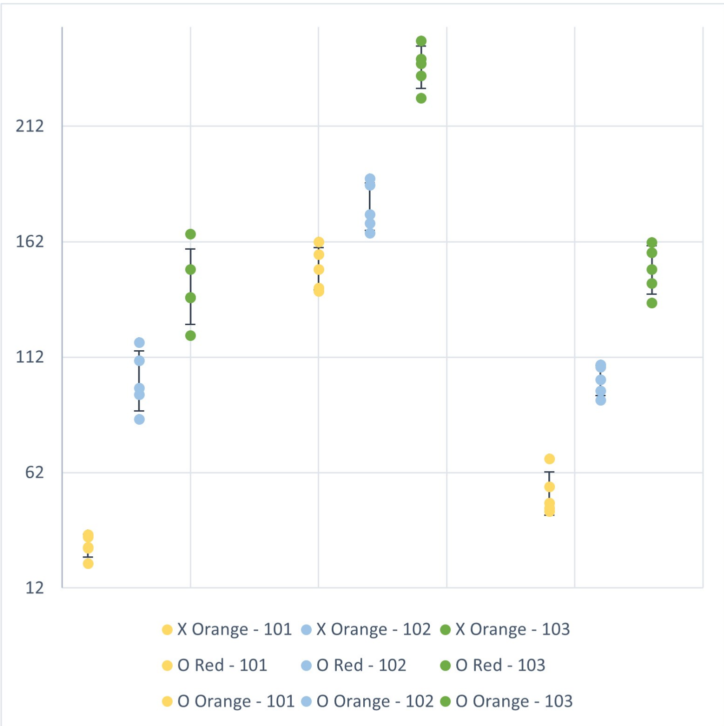

Figure 3.60: The graph reports in yellow the points obtained from the exercise with 101 level of force, in blue the points from the 102 level of force and in green the points from the 103 level of force. The first column represents the O RED points, the second column represents the X ORANGE points and the third column represents the O ORANGE points. The black lines indicate the standard deviation of each point from their average.

Using the average values, we plotted the average second peaks for the Wide stance squat:

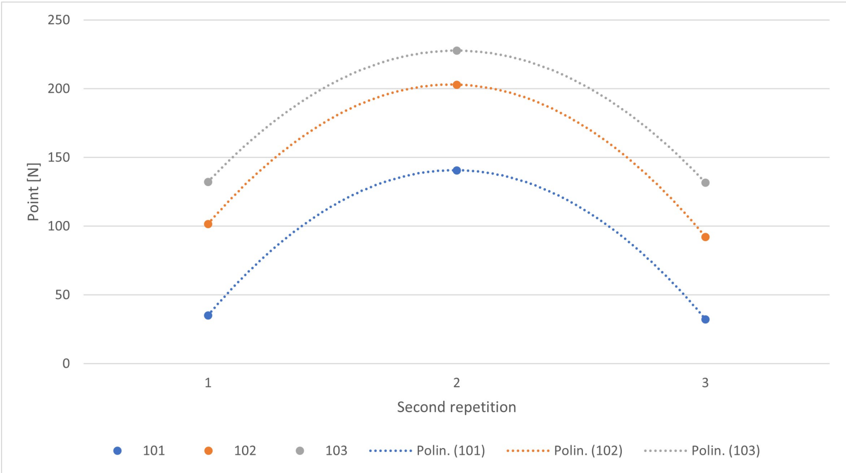

Figure 3.61: In blue the average second peak of the Ground Reaction Force with 101 force, in orange the average second peak of the Ground Reaction Force with 102 force, and in grey the average second peak of the Ground Reaction Force with 103 force.

As we would have liked, we obtained that the exercise with 101 level of force is higher than the other two, and the second peak for the exercise with 102 level of force is higher than the ones with 103 level of force.

From here, we calculated the standard deviation between the different curves with respect to the three points.

	o RED	x ORANGE	o ORANGE
101-102 [N]	36,93	33,40	34,32
101-103 [N]	52,63	46,85	54,69
102-103 [N]	19,62	14,47	23,18

Table 3.10: The first row considers the standard deviation between the three points with 101 and 102 force. The second row considers the standard deviation between the three points with 101 and 103 force. The third row considers the standard deviation between the three points with 102 and 103 force.

To have a final ideal, we obtain the average of the standard deviation for each of the points:

101-102 [N]	101-103 [N]	102-103 [N]
34,88	51,39	19,09

Table 3.11: The first row considers the standard deviation between the exercises with 101 and 102 force. The second row considers the standard deviation between the exercises with 101 and 103 force. The third row considers the standard deviation between the exercises with 102 and 103 force.

As we expected, the higher deviation is between the exercise with 101 force and the one with 103 force, since there is a higher difference in force.

3.3.3. Rotational Arm Position

In this section, we want to consider the evolution of the Rotation Arm Position and how it is different with respect to the three levels of force.

101 level force

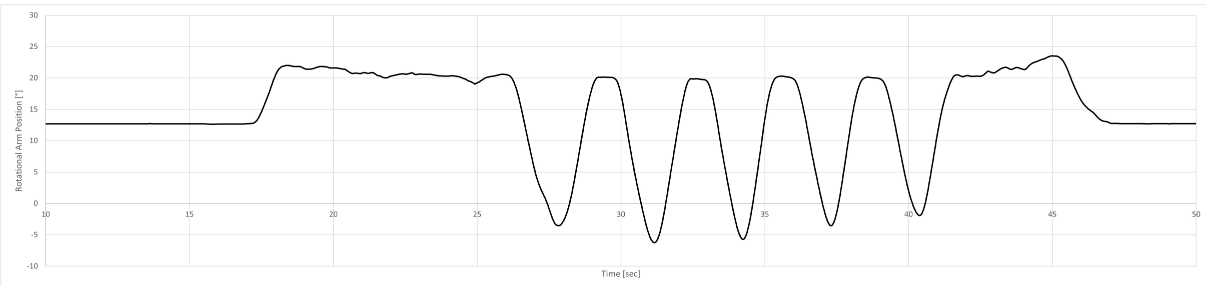

Figure 3.62: Rotational Arm Position evolution with the level of the force 101.

102 level force

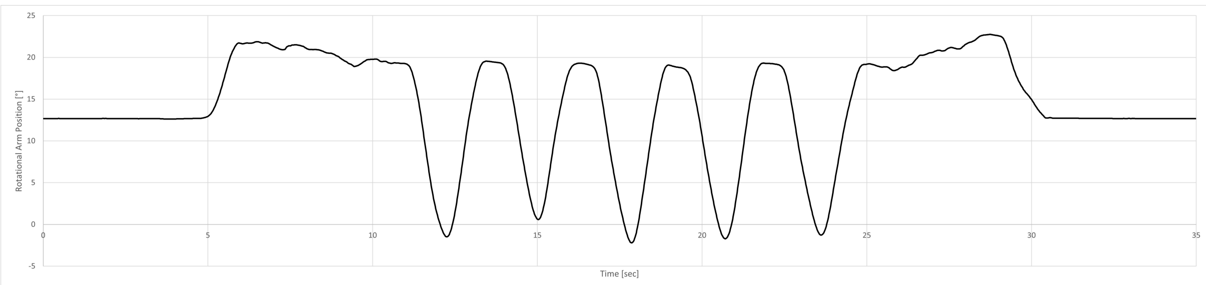

Figure 3.63: Rotational Arm Position evolution with the level of the force 102.

103 level force

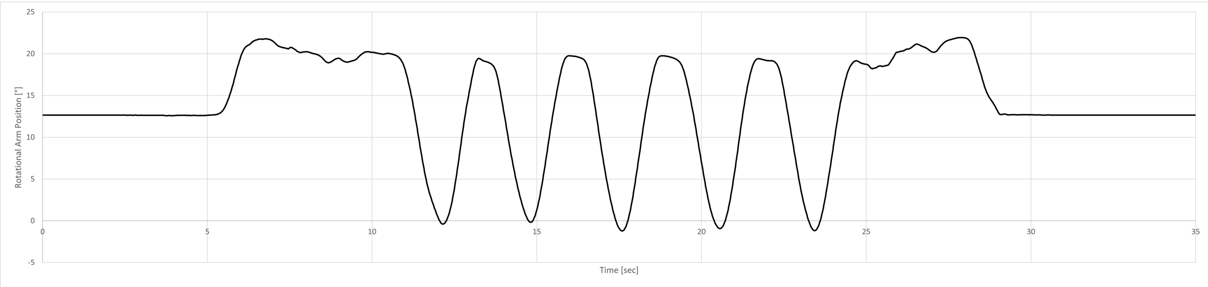

Figure 3.64: Rotational Arm Position evolution with the level of the force 103.

Explanation of the Rotational Arm Position

The evolutions of the Rotational Arm Position are similar to the ones for the Bar Height, this is why they depend on the flexions and extensions of the subject. As before, the maximum values for all three levels of force are very similar to each other for all the repetitions. It means that the subject returns at the same level at the end of the extension. Instead, the minimum values are less constant between the three different exercises. It means that the subject doesn't have the same knee flexion for all the repetitions.

In the histogram, we can see in the same graphs the values of the maximum and minimum of the Rotational Arm Position for the three levels of force.

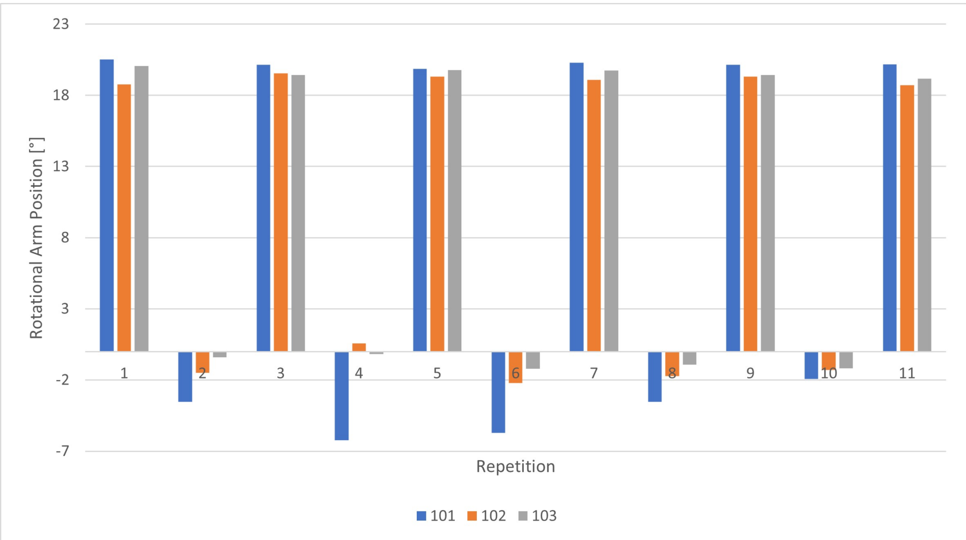

Figure 3.65: In blue the Rotational Arm Position values with 101 force, in orange the Rotational Arm Position values with 102 force, and in grey the Rotational Arm Position values with 103 force.

3.3.4. Bar Angle Position

In this section, we want to consider the evolution of the Bar Angle Position and how it is different with respect to the three levels of force.

101 level force

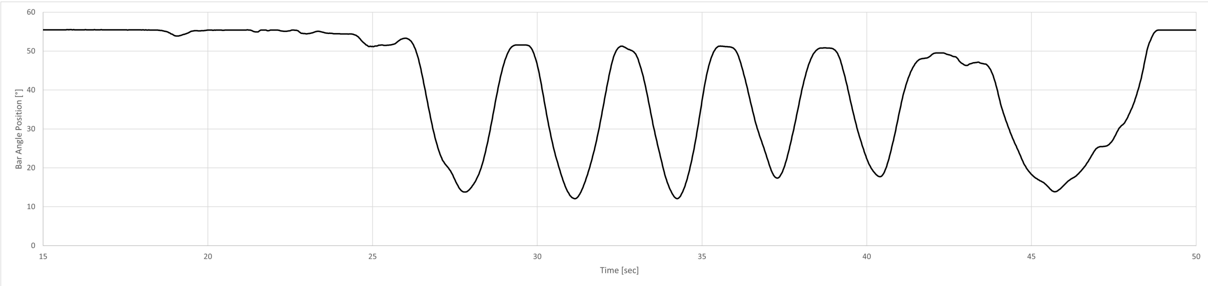

Figure 3.66: Bar Angle Position evolution with the level of the force 101.

102 level force

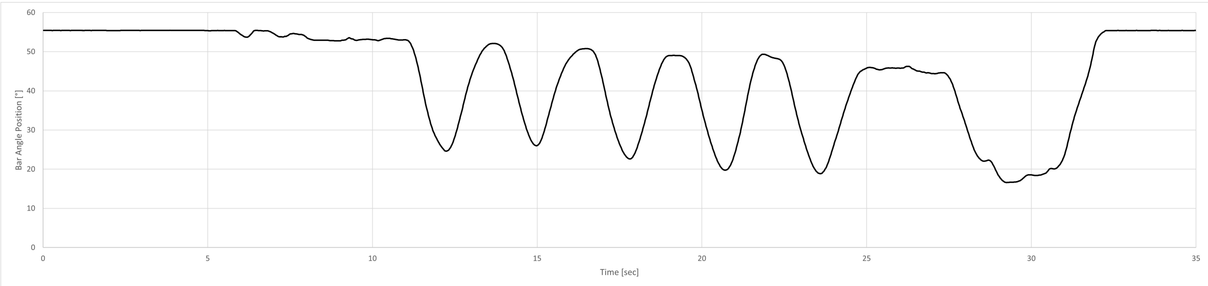

Figure 3.67: Bar Angle Position evolution with the level of the force 102.

103 level force

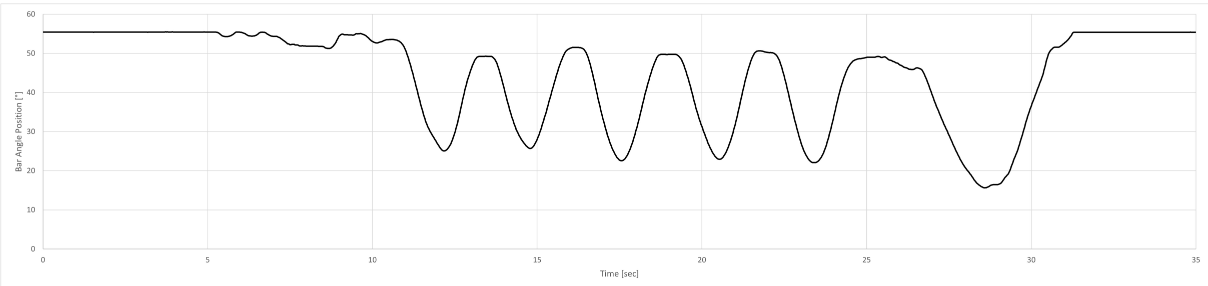

Figure 3.68: Bar Angle Position evolution with the level of the force 103.

Explanation of the Bar Angle Position

The evolutions of the Bar Angle Position are similar to the ones for the Bar Height, this is why they depend on the flexions and extensions of the subject. As before, the maximum values for all three levels of force are very similar to each other for all the repetitions. It means that the subject returns at the same level at the end of the extension. Instead, the minimum values are less constant between the three different exercises. It means that the subject doesn't have the same knee flexion for all the repetitions.

In the histogram, we can see in the same graphs the values of the maximum and minimum of the Bar Angle Position for the three levels of force.

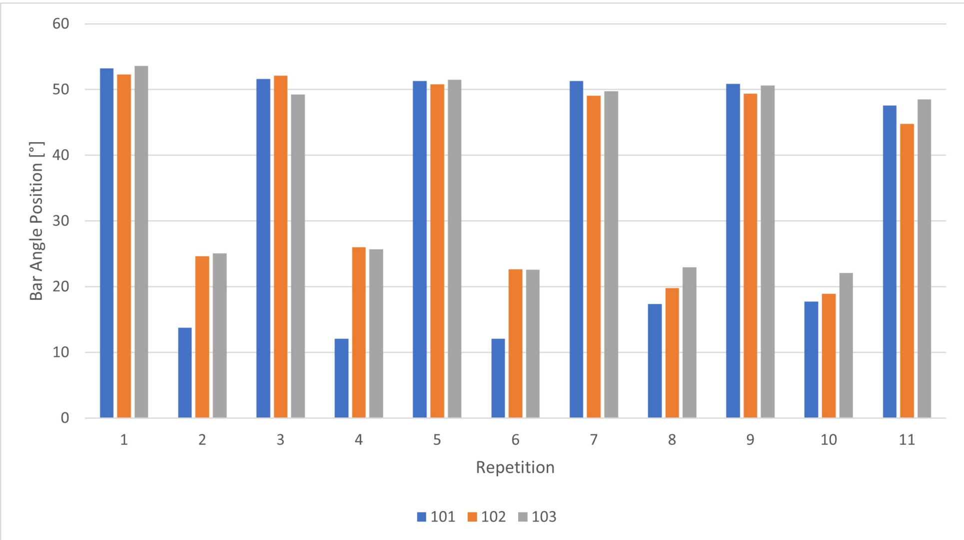

Figure 3.69: In blue the Bar Angle Position values with 101 force, in orange the Bar Angle Position values with 102 force, and in grey the Rotational Bar Angle values with 103 force.

3.4. Deadlift

3.4.1. Ground Reaction Force

We need to hand up a few steps in order to study the evolution of the Ground Reaction Force. The signal from the data was characterized by noise; for this, we implemented a code on Phyton to figure out a good signal where it was possible to identify four main points:

- X RED identifies the maximum value on the big peak
- X ORANGE identifies the maximum value on the small peak
- O RED identifies the minimum value before the X ORANGE point
- O ORANGE identifies the minimum value after the X ORANGE point

Since the Deadlift exercise was done for three different levels of force applied to the trapezius muscle, we are going to visualize the evolution of the Ground Reaction Force for each level.

101 level force

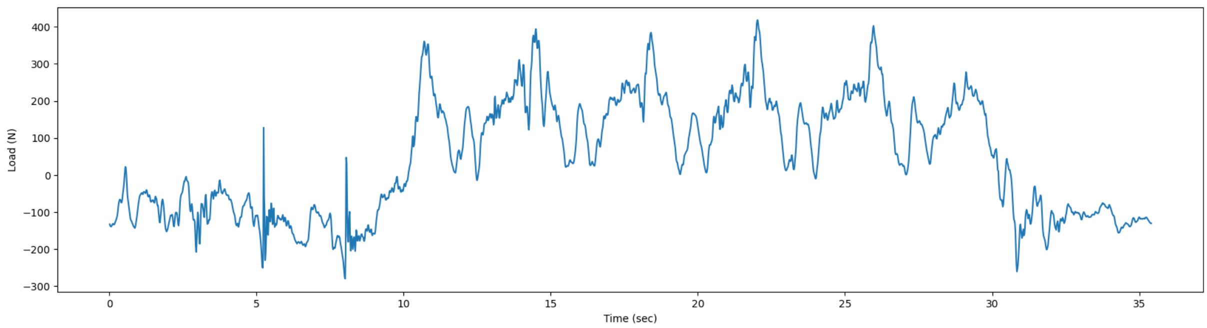

Figure 3.70: Ground Reaction Force original signal for Deadlift with 101 level of force.

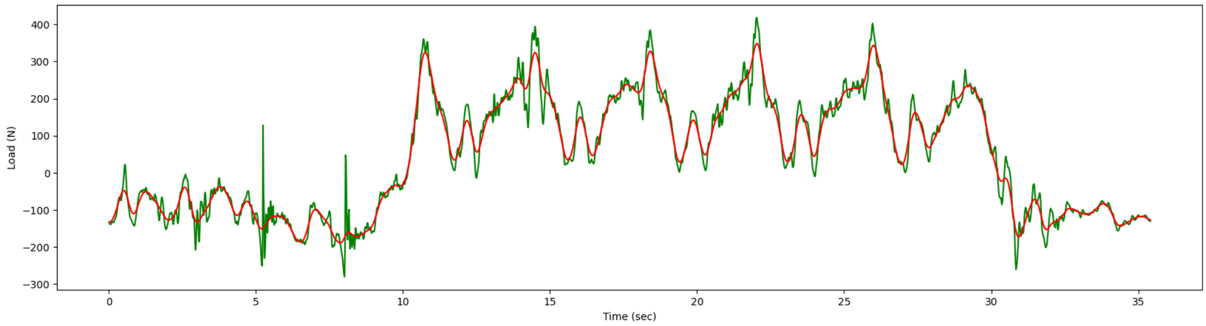

Figure 3.71: In green is the Ground Reaction Force original signal and in red is the Ground Reaction Force filtered signal.

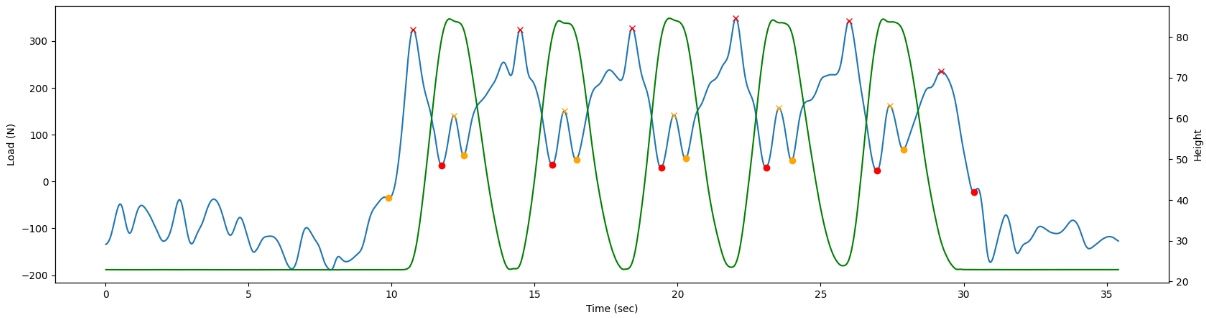

Figure 3.72: In blue the evolution of the load with 101 force, in green the evolution of the bar height with 101 force, x RED the maximum peaks, x ORANGE the second maximum peaks because of the contraction of the muscle, o RED the minimum peaks after the maximum peaks (x RED) and, o ORANGE the minimum peaks after the second maximum peaks (x ORANGE).

102 level force

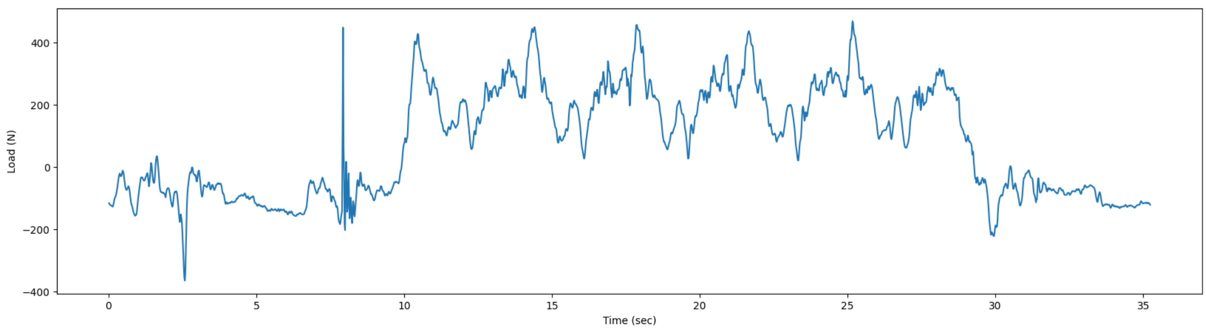

Figure 3.73: Ground Reaction Force original signal for Deadlift with 102 level of force.

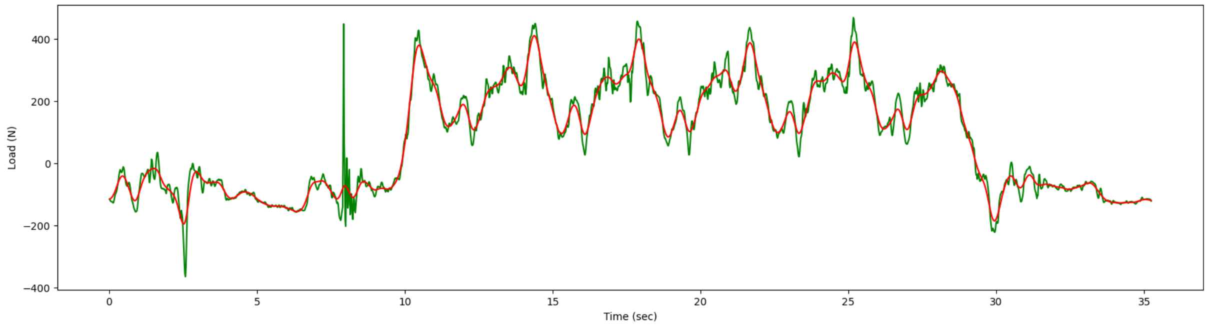

Figure 3.74: In green is the Ground Reaction Force original signal and in red is the Ground Reaction Force filtered signal.

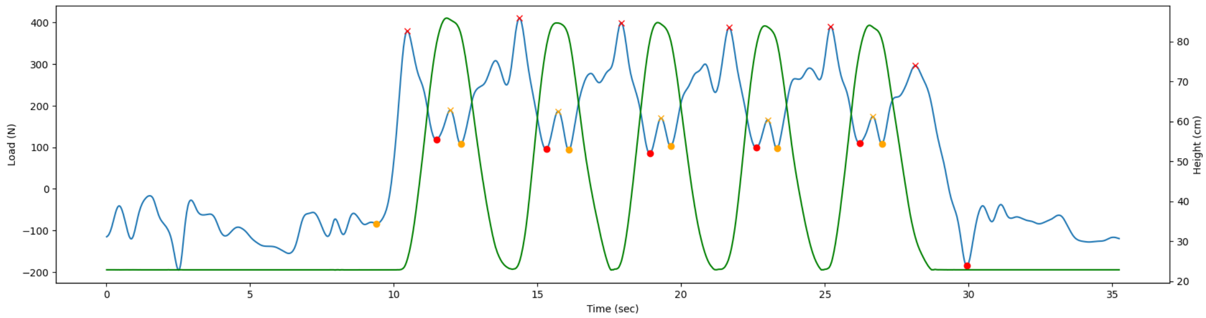

Figure 3.75: In blue the evolution of the load with 102 force, in green the evolution of the bar height with 102 force, x RED the maximum peaks, x ORANGE the second maximum peaks because of the contraction of the muscle, o RED the minimum peaks after the maximum peaks (x RED) and, o ORANGE the minimum peaks after the second maximum peaks (x ORANGE).

103 level force

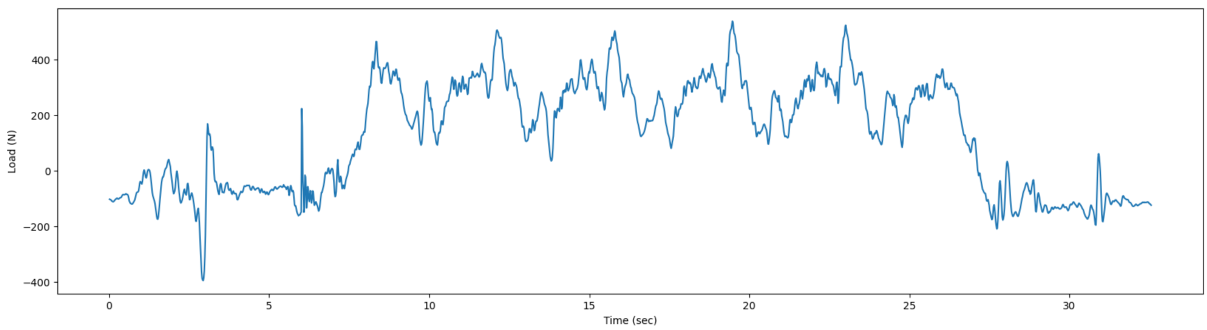

Figure 3.76: Ground Reaction Force original signal for Deadlift with 103 level of force.

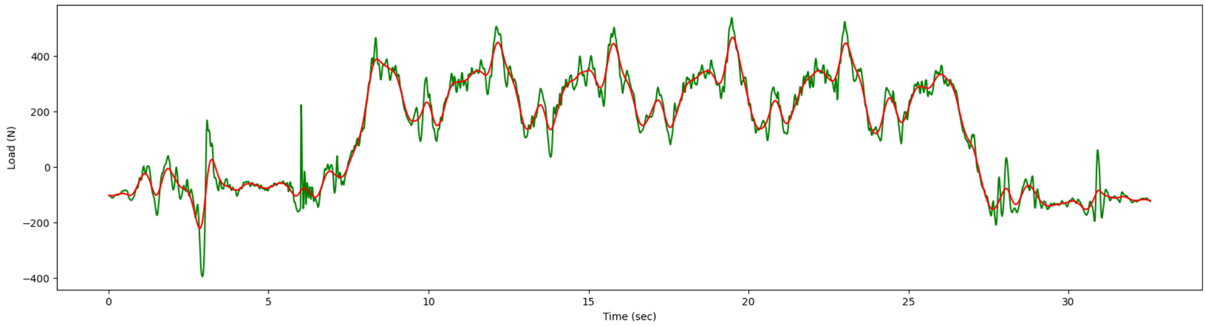

Figure 3.77: In green is the Ground Reaction Force original signal and in red is the Ground Reaction Force filtered signal.

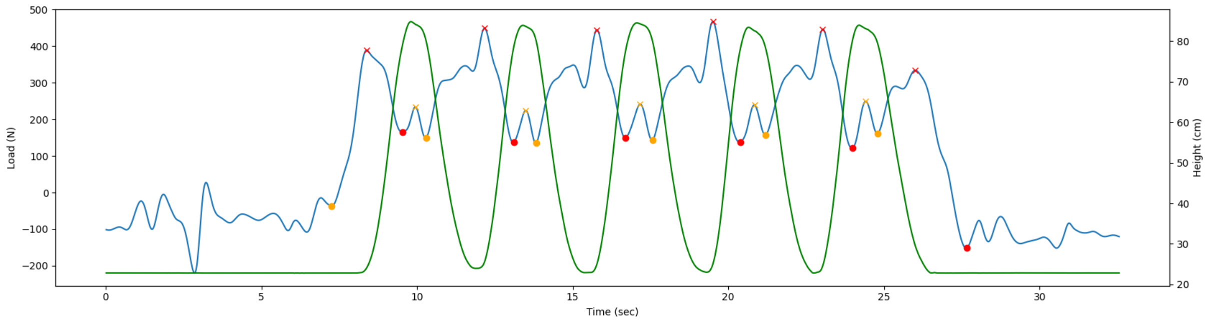

Figure 3.78: In blue the evolution of the load with 1043force, in green the evolution of the bar height with 103 force, x RED the maximum peaks, x ORANGE the second maximum peaks because of the contraction of the muscle, o RED the minimum peaks after the maximum peaks (x RED) and, o ORANGE the minimum peaks after the second maximum peaks (x ORANGE).

Explanation of the Ground Reaction Force

We want to focus our attention on the last graph for each level of force, see Figure 3.72, Figure 3.75 and Figure 3.78. The blue line is the evolution of the Ground Reaction Force, and in the same graph is also plotted the Bar Height signal to understand the timing of the exercise. The subject starts by standing down, where the Ground Reaction Force is low. While knee flexion exists, the Ground Reaction Force increases until a maximum point, identified in the graph as x RED. During the extension, the quadriceps and gluteal muscles work. During the flexion, the muscles acting are the hamstrings and adductors. Between the extension and flexion movement, we can consider a second peak (identified with the x ORANGE point, such as the minimum peak after the maximum peak (x RED)) due to the inertial force and co-contraction of the muscles (see Materials and Methods chapter). We are considering the Deadlift, where the small peaks (identified by the o RED, x ORANGE, and o ORANGE points) are at the end of the extension.

3.4.2. Bar Height

Since the Bar Height signal is already reported with the Ground Reaction Force evolution, see Figure 3.72, Figure 3.75 and Figure 3.78, in this section we want to focus on the maximum and minimum values of the Bar Height for the three level of forces.

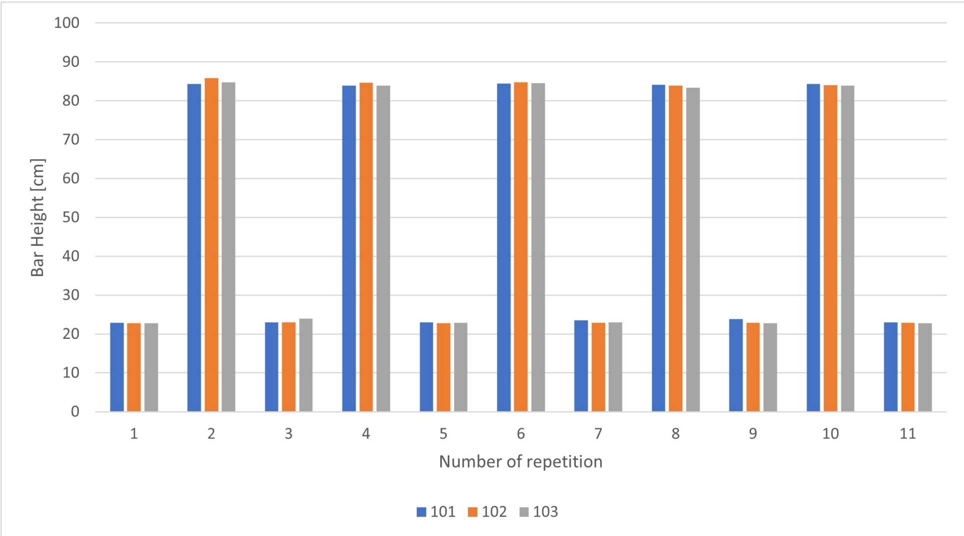

Figure 3.79: In blue the Bar Height values with 101 force, in orange the Bar Height values with 102 force, and in grey the Bar Height values with 103 force.

We can consider that the maximum values of the Bar Height for all three levels of force are very similar to each other for all the repetitions. It means that the subject returns at the same level at the end of the extension. The same situation is for the minimum values of the Bar Height, the subject returns at the same level at the end of the flexion.

Relationship between Ground Reaction Force and Bar Height

One of the main aims of the thesis is to study how the two peaks that characterized the Ground Reaction Force behave, changing along the different type of exercise and level of force.

First of all, we focus on the second peak, the small one designed by o RED, x ORANGE, and o ORANGE points. As already described in the Materials and Methods section, the presence of the second peaks is due to inertial force and the co-contraction of the muscles because the subject changes movement. In the Deadlift, the second peak is while changing movement from extension to flexion at the level of the maximum values of the Bar Height. We visualized a strong relationship between the values of the second peaks with the values of the Bar Height. We thought that, in general, with a higher force, the second peaks should be higher than the ones with an lower force. So, we could expect that the second peak for the exercise with 103 level of force should be higher than the other two, and the second peak for the exercise with 102 level of force should be higher than the ones with 101 level of force.

However, if we plot the second peaks repetition by repetition, we can see that this assumption was correct. Here we reported the graphs:

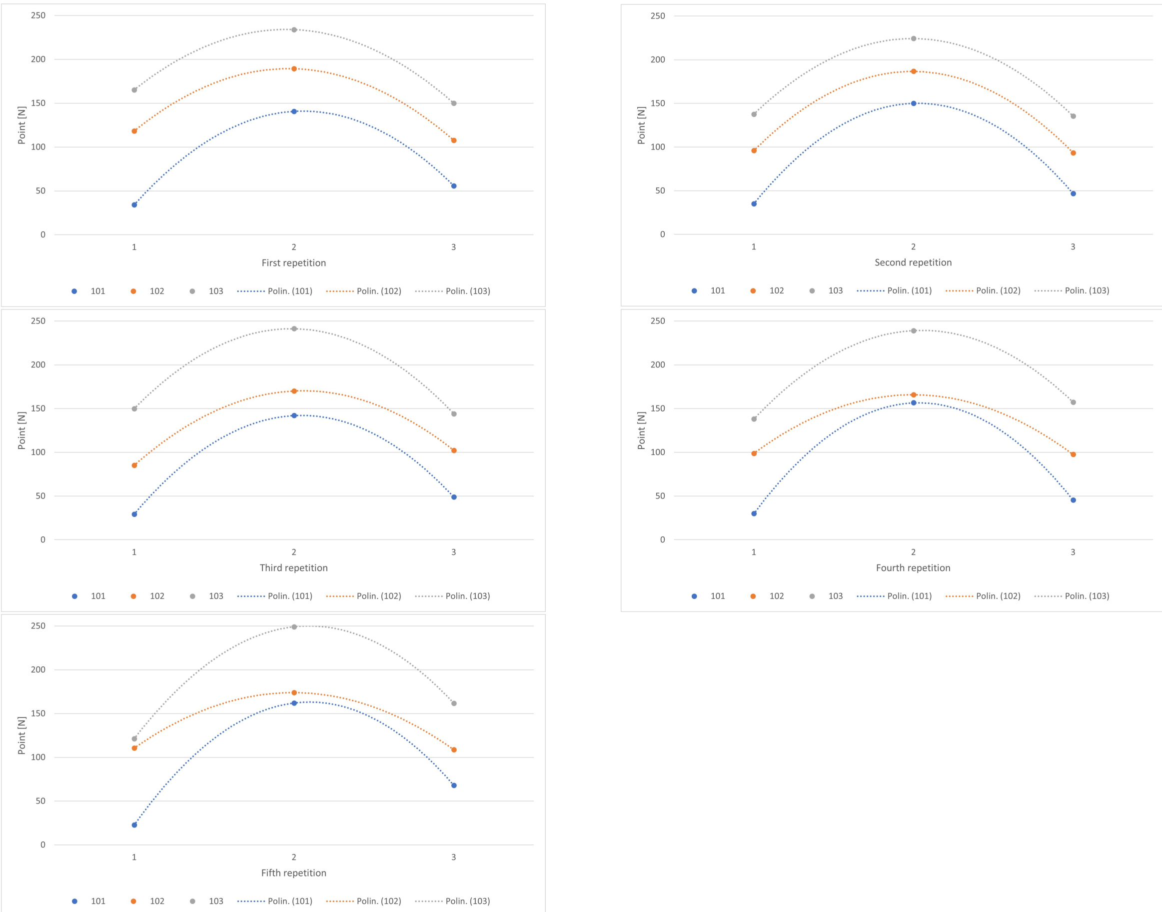

Figure 3.80: Considering each repetition, in blue the second peak of the Ground Reaction Force with 101 force, in orange the second peak of the Ground Reaction Force with 102 force, and in grey the second peak of the Ground Reaction Force with 103 force.

Even if the behavior of the second peaks for the Single leg squat was not the same for all the repetitions because of the different flexions made by the subject, for the Deadlift the behavior of the second peaks is the same for all the repetitions. As we can see in

Figure 3.79, the subject reaches very few different levels of the flexions for the different repetitions. Thanks to this quite constant behavior the second peaks are coherent for each repetition.

As explained in the Materials and Methods section, if a person performs a squat with a quick and explosive movement, the quadriceps muscles may contract rapidly and generate a secondary peak in the force curve. Alternatively, if a person performs a squat with a slower and more controlled movement, the hamstrings and gluteal muscles may contract more gradually, resulting in a smoother and more gradual decrease in the Ground Reaction Force.

To study this behavior, we calculate the difference between the maximum point (x RED) and the second maximum point (x ORANGE) identified in the Ground Reaction Force. In the graph below, we want to do a comparison of this difference with respect to the three levels of force used for the exercise.

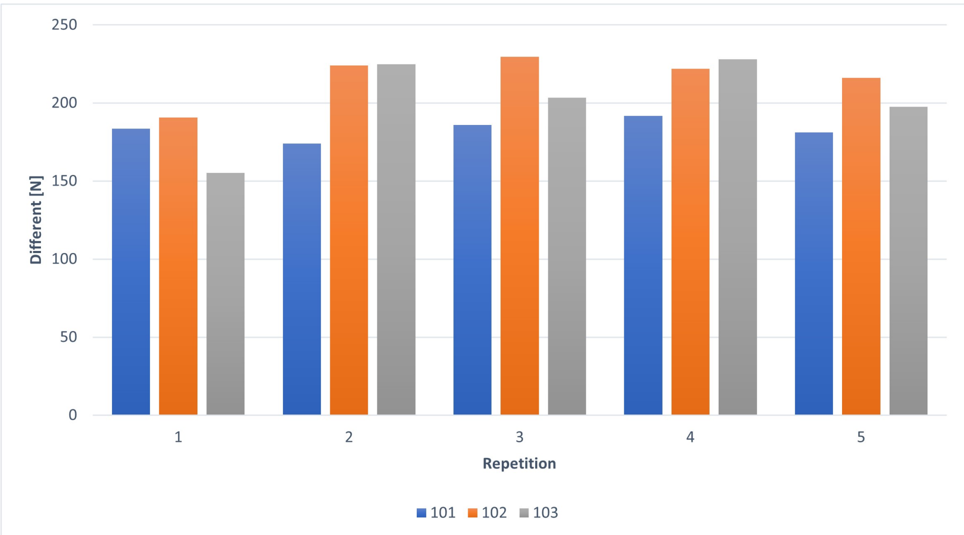

Figure 3.81: In blue the difference between x RED and x ORANGE with 101 force, in orange the difference between x RED and x ORANGE with 102 force, and in grey the difference between x RED and x ORANGE with 103 force.

The higher the distance, the lower the x ORANGE point, which means that the second peaks are lower. From this result, we can say that the distances are in general higher for the 102 level of force because the squat is more quick and explosive. Instead, from the previous exercises, we obtained higher differences for the 103 level of force. In this case, the distances are in general lower for the 103 level of force because the squat is slower and more controlled. In any case, repetition by repetition is better to check the different behavior.

Another important parameter to take into consideration is the height in terms of the Ground Reaction Force of the first peak, indicated by the x RED point. There is this peak at the end of the flexion, and as we could expect, the exercise with 103 level of force has higher values of x RED points because there is more weight. As we saw in Figure 3.79, the level of the extension doesn't change with respect to the level of force, it means that the x RED values don't depend on the Bar Height. Here are reported the x RED evolution:

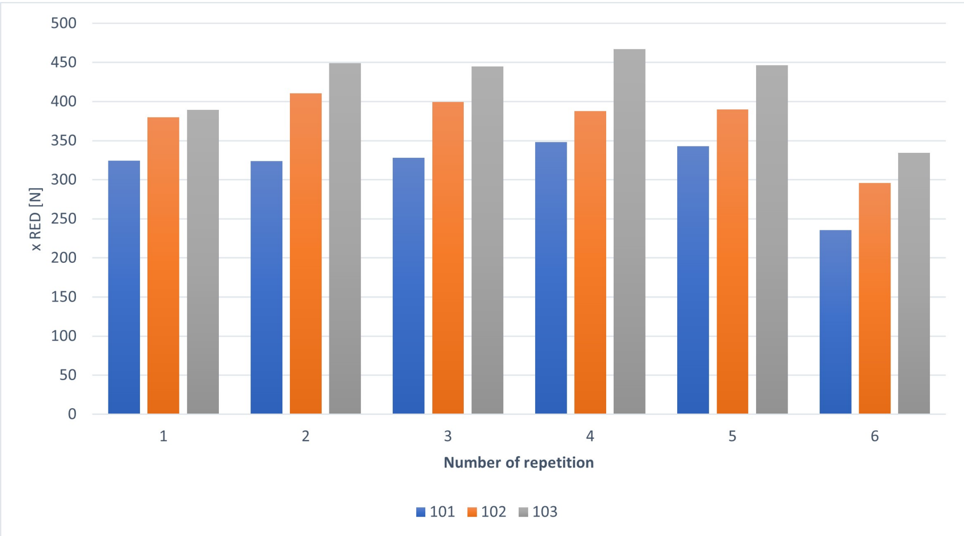

Figure 3.82: In blue the x RED peak with 101 force, in orange the x RED peak with 102 force, and in grey the x RED peak with 103 force.

Deviation of the second peaks concerning the level of the force

In order to obtain a statistical behavior of the second peaks in the Ground Reaction Force, we calculated the average of the points that identified the curve and obtained the standard deviation between the three levels of force. With this approach, we can evaluate how the Ground Reaction Force changes facing the same exercise but having different forces at the level of the trapezius muscle.

In the tables below, we reported the averages and the standard deviation of the three points that define the second peaks depending on the level of force.

	o RED	x ORANGE	o ORANGE
101 force [N]	30,26±4,94	150,23±9,18	52,96±9,40
102 force [N]	101,73±12,97	177,15±10,34	101,95±6,56
103 force [N]	142,48±16,33	237,53±9,22	149,80±10,48

Table 3.12: Considering the three levels of the force, the table reports the average (first number) and the standard deviation (second number) of the three points that define the second peaks.

To visualize better the evolution of the point values that identify the second peak, we plotted the following graph:

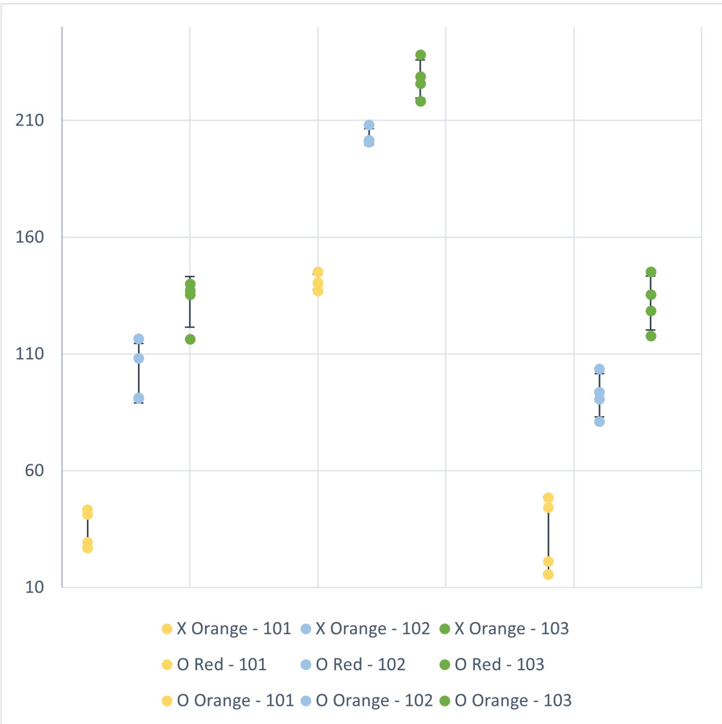

Figure 3.83: The graph reports in yellow the points obtained from the exercise with 101 level of force, in blue the points from the 102 level of force and in green the points from the 103 level of force. The first column represents the O RED points, the second column represents the X ORANGE points and the third column represents the O ORANGE points. The black lines indicate the standard deviation of each point from their average.

Using the average values, we plotted the average second peaks for the Deadlift:

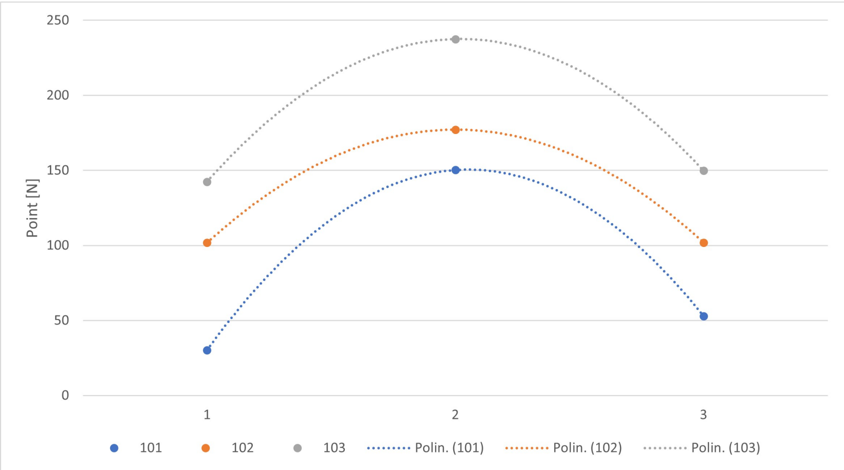

Figure 3.84: In blue the average second peak of the Ground Reaction Force with 101 force, in orange the average second peak of the Ground Reaction Force with 102 force, and in grey the average second peak of the Ground Reaction Force with 103 force.

As we would have liked, we obtained that the exercise with 101 level of force is higher than the other two, and the second peak for the exercise with 102 level of force is higher than the ones with 103 level of force.

From here, we calculated the standard deviation between the different curves with respect to the three points.

	o RED	x ORANGE	o ORANGE
101-102 [N]	38,79	16,92	26,93
101-103 [N]	60,23	46,82	51,90
102-103 [N]	25,58	33,14	26,53

Table 3.13: The first row considers the standard deviation between the three points with 101 and 102 force. The second row considers the standard deviation between the three points with 101 and 103 force. The third row considers the standard deviation between the three points with 102 and 103 force.

To have a final ideal, we obtain the average of the standard deviation for each of the points:

101-102 [N]	101-103 [N]	102-103 [N]
27,55	52,98	28,42

Table 3.14: The first row considers the standard deviation between the exercises with 101 and 102 force. The second row considers the standard deviation between the exercises with 101 and 103 force. The third row considers the standard deviation between the exercises with 102 and 103 force.

As we expected, the higher deviation is between the exercise with 101 force and the one with 103 force, since there is a higher difference in force.

3.4.3. Rotational Arm Position

In this section, we want to consider the evolution of the Rotation Arm Position and how it is different with respect to the three levels of force.

101 level force

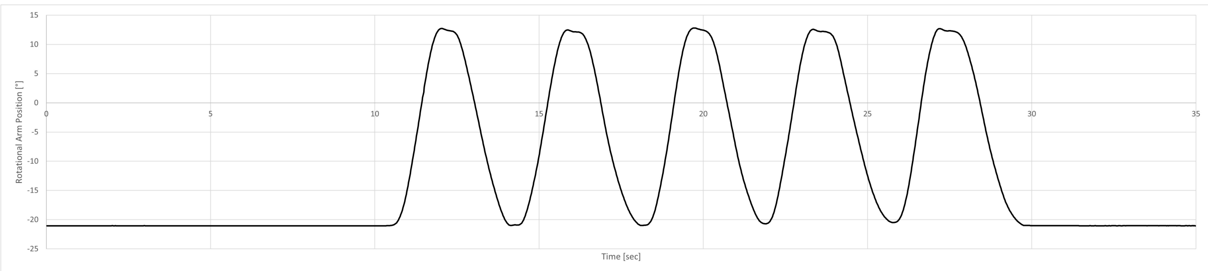

Figure 3.85: Rotational Arm Position evolution with the level of the force 101.

102 level force

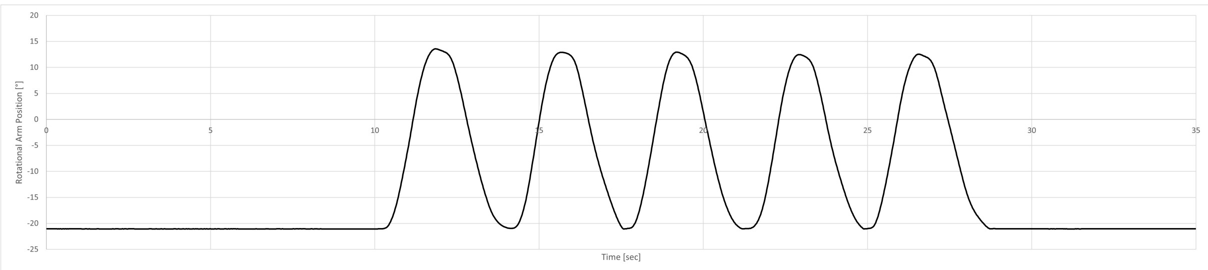

Figure 3.86: Rotational Arm Position evolution with the level of the force 102.

103 level force

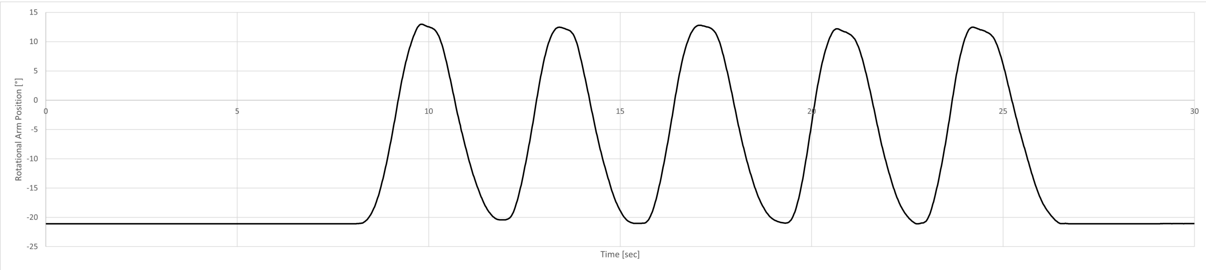

Figure 3.87: Rotational Arm Position evolution with the level of the force 103.

Explanation of the Rotational Arm Position

The evolutions of the Rotational Arm Position are similar to the ones for the Bar Height, this is why they depend on the flexions and extensions of the subject. As before, the maximum and minimum values for all three levels of force are very similar to each other for all the repetitions. It means that the subject returns at the same level at the end of the extension and at the end of the extension. The same situation is for the minimum values of the Bar Height, the subject returns at the same level at the end of the flexion.

In the histogram, we can see in the same graphs the values of the maximum and minimum of the Rotational Arm Position for the three levels of force.

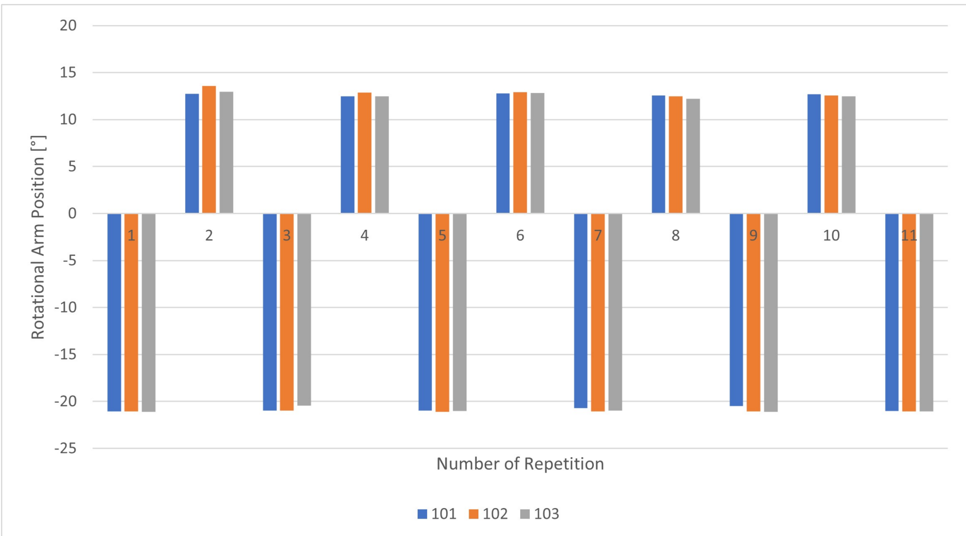

Figure 3.88: In blue the Rotational Arm Position values with 101 force, in orange the Rotational Arm Position values with 102 force, and in grey the Rotational Arm Position values with 103 force.

3.4.4. Bar Angle Position

In this section, we want to consider the evolution of the Bar Angle Position and how it is different with respect to the three levels of force. In this case, since the variation of the Bar Angle was very small, the signal was characterized by noise. We preferred to filter the signal to visualize a more smooth evolution.

101 level force

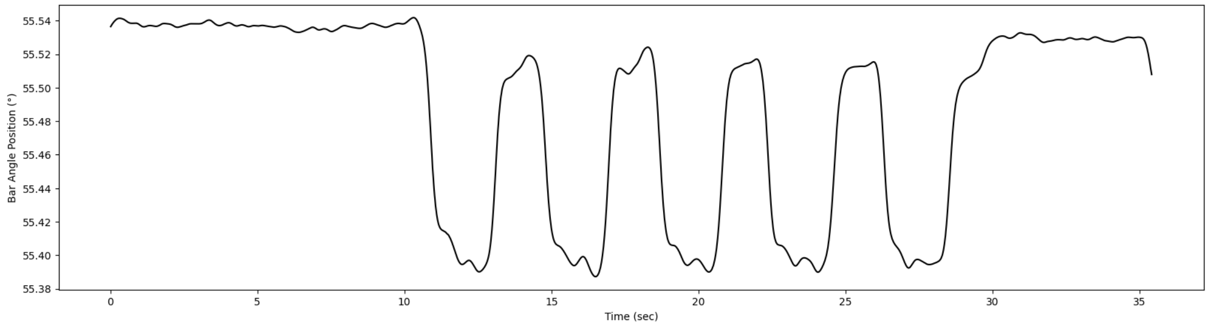

Figure 3.89: Bar Angle Position evolution with the level of the force 101.

102 level force

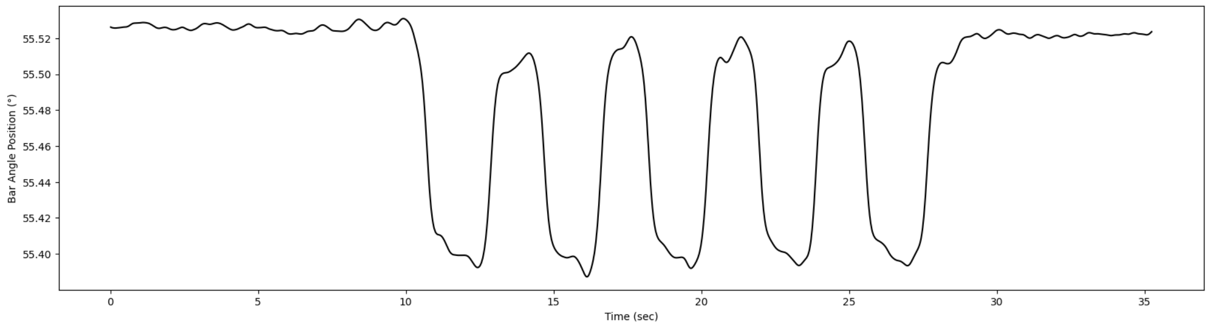

Figure 3.90: Bar Angle Position evolution with the level of the force 102.

103 level force

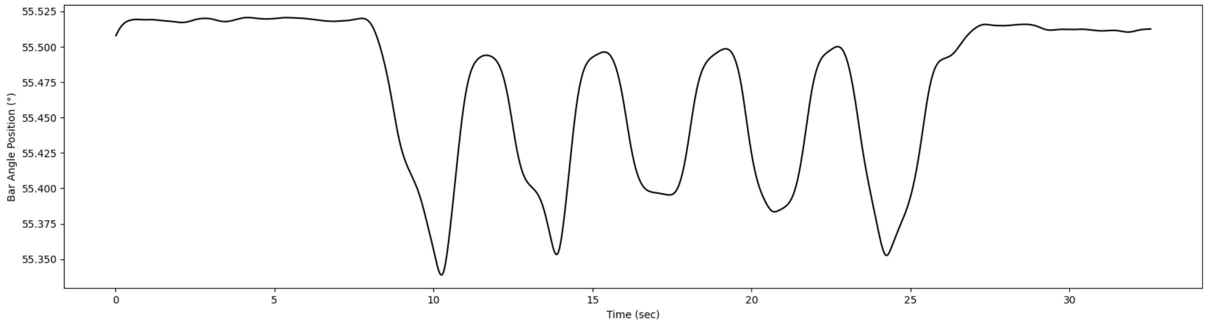

Figure 3.91: Bar Angle Position evolution with the level of the force 103.

Explanation of the Bar Angle Position

The evolutions of the Bar Angle Position are similar to the ones for the Bar Height, this is why they depend on the flexions and extensions of the subject. As before, the maximum and minimum values for all three levels of force are very similar to each other for all the repetitions. It means that the subject returns at the same level at the end of the extension and at the end of the flexion. The same situation is for the minimum values of the Bar Height, the subject returns at the same level at the end of the flexion.

In the histogram, we can see in the same graphs the values of the maximum and minimum of the Bar Angle Position for the three levels of force.

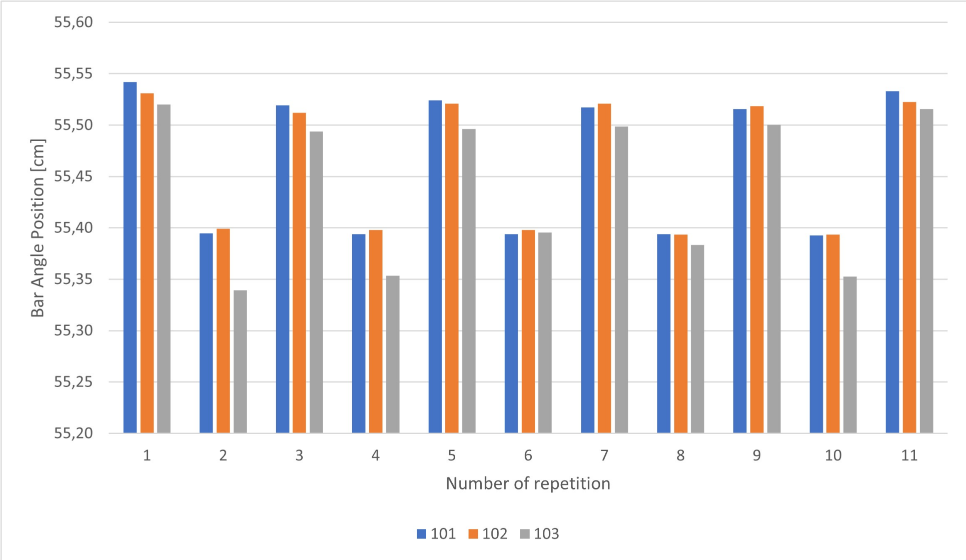

Figure 3.92: In blue the Bar Angle Position values with 101 force, in orange the Bar Angle Position values with 102 force, and in grey the Rotational Bar Angle values with 103 force.

3.5. Comparison between the exercises

In this section, we are going to study how the Ground Reaction Force change considering the same level of force between the different exercises.

3.5.1. 101 level force

In order to obtain a statistical behavior of the second peaks in the Ground Reaction Force, we calculated the average of the points that identified the curve and obtained the standard deviation between the four different exercises. With this approach, we can evaluate how the Ground Reaction Force changes having the same level of force at the level of the trapezius muscle but facing different exercises.

We have already reported the average and the standard deviation of each point that identifies the second peak for each exercise and level of force 3.4.2 - 3.3.2 - 3.1.2 - 3.2.2. Here we want to visualize the evolution of the point values with respect to the different exercises and maintaining as 101 is the level of force.

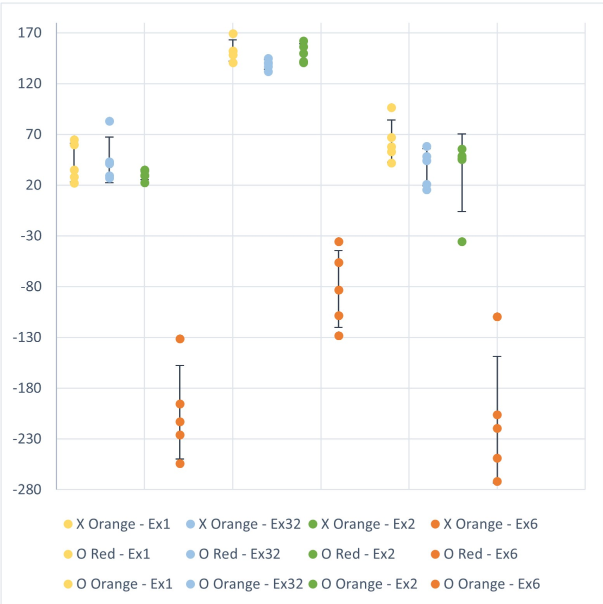

Figure 3.93: The graph reports in yellow the points obtained from the Normal stance squat exercise, in blue the points from the Wide stance squat exercise, in green the points from the Deadlift exercise and in orange the points from the Single leg squat exercise. The first column represents the O RED points, the second column represents the X ORANGE points and the third column represents the O ORANGE points. The black lines indicate the standard deviation of each point from their average.

Using the averages of the three points that define the second peaks depending on the exercise that we have already studied in the previous sections, we plotted the average second peaks for the four exercises maintaining 101 as the level of the force:

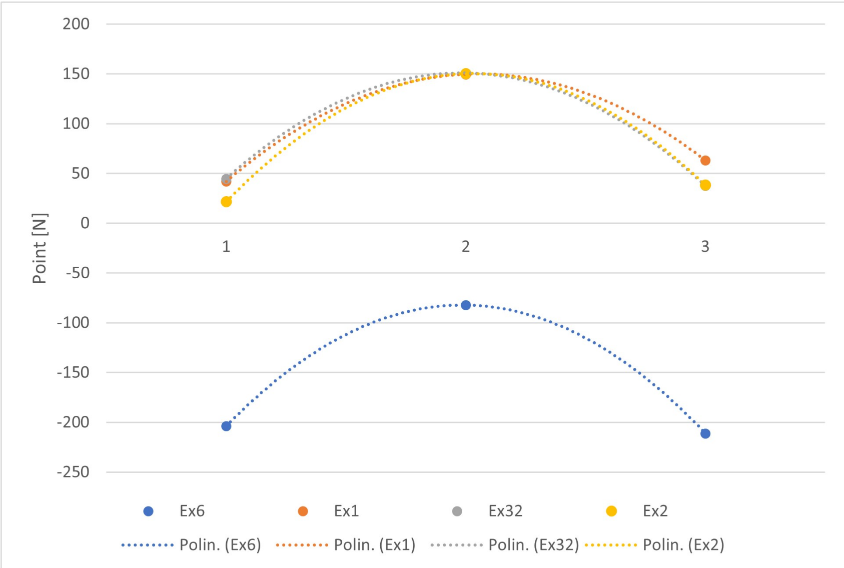

Figure 3.94: In blue the average second peak of the Ground Reaction Force for Single leg squat (Ex6), in orange the average second peak of the Ground Reaction Force for the Normal stance squat (Ex1), in grey the average second peak of the Ground Reaction Force for the Wide stance squat (Ex32), and in yellow the average second peak of the Ground Reaction Force for the Deadlift (Ex2).

We obtained that the Wide stance squat (Ex32), Normal stance squat (Ex1), and Deadlift (Ex2) average second peaks are higher than the Single leg squat (Ex6) average peak. The second peaks for the Single leg squat are at the end of the extension, instead, for the other exercise the second peaks are at the end of the flexion, and for this reason the curve for the Single leg squat is in the negative interval of values.

From here, we calculated the standard deviation between the different curves with respect to the three points and the average of the standard deviation for each of the points:

Ex6-Ex1 [N]	Ex6-Ex32 [N]	Ex6-Ex2 [N]	Ex32-Ex1 [N]	Ex1-Ex2 [N]	Ex32-Ex2 [N]
136,20	133,08	128,62	21,34	21,59	24,91

Table 3.15: The first column considers the standard deviation between the Single leg squat (Ex6) and the Normal stance squat (Ex1). The second column considers the standard deviation between the Single leg squat (Ex6) and Wide stance squat (Ex32). The third column considers the standard deviation between the Single leg squat (Ex6) and Deadlift (Ex2). The fourth column considers the standard deviation between the Wide stance squat (Ex32) and Normal stance squat (Ex1). The fifth column considers the standard deviation between the Normal stance squat (Ex1) and Deadlift (Ex2). The sixth column considers the standard deviation between the Wide stance squat (Ex32) and Deadlift (Ex2).

As we expected, the higher deviation is between the Single leg squat and the others. Instead, the other deviations are very similar and quite small.

Another important parameter to take into consideration is the height in terms of the Ground Reaction Force of the first peak, indicated by the x RED point. This peak is peak at the end of the extension for the Ex6 and at the and of the flexion for the other exercises. Here are reported the x RED evolution:

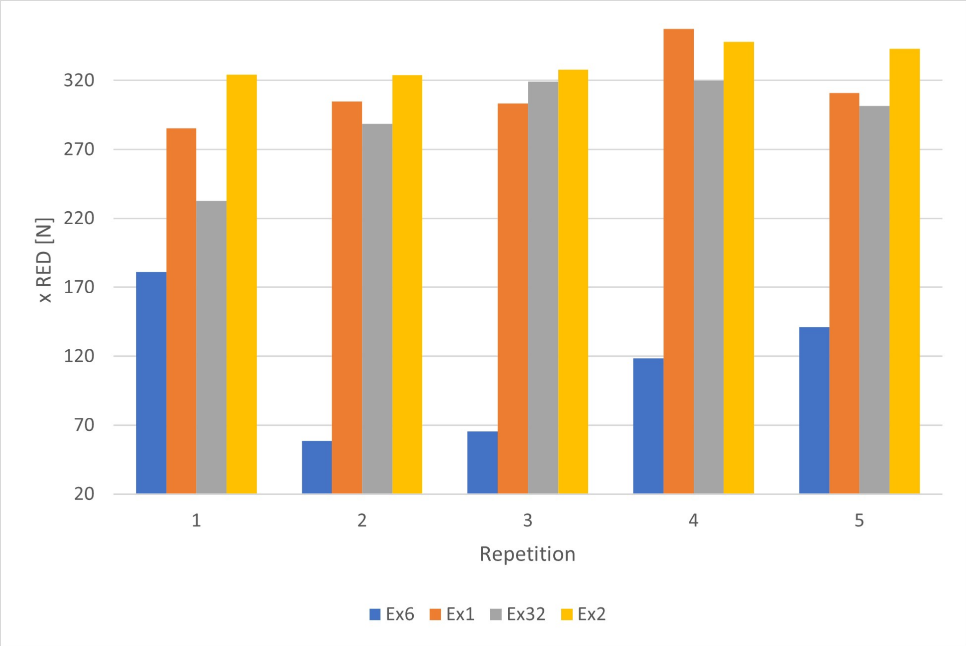

Figure 3.95: In blue the x RED peak for the Single leg squat (Ex6), in orange the x RED peak for the Normal stance squat (Ex1), in grey the x RED peak for the Wide stance squat (Ex32), and in yellow the x RED peak for the Deadlift (Ex2).

As we expected the values of the x RED for the Single leg squat are lower than the others, and we can see that with the Deadlift we obtain higher values of first peaks.

3.5.2. 102 level force

In order to obtain a statistical behavior of the second peaks in the Ground Reaction Force, we calculated the average of the points that identified the curve and obtained the standard deviation between the four different exercises. With this approach, we can evaluate how the Ground Reaction Force changes having the same level of force at the level of the trapezius muscle but facing different exercises.

We have already reported the average and the standard deviation of each point that identifies the second peak for each exercise and level of force 3.4.2 - 3.3.2 - 3.1.2 - 3.2.2. Here we want to visualize the evolution of the point values with respect to the different exercises and maintaining as 102 is the level of force.

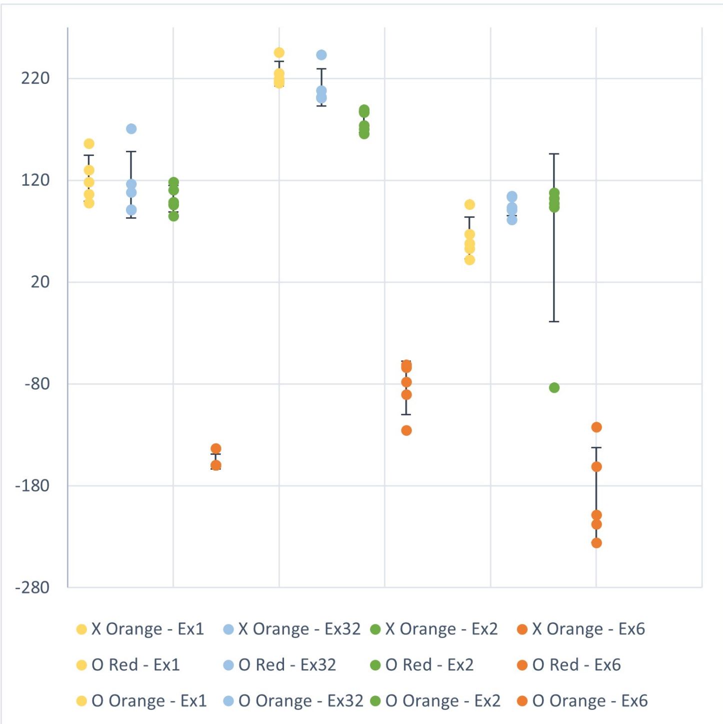

Figure 3.96: The graph reports in yellow the points obtained from the Normal stance squat exercise, in blue the points from the Wide stance squat exercise, in green the points from the Deadlift exercise and in orange the points from the Single leg squat exercise. The first column represents the O RED points, the second column represents the X ORANGE points and the third column represents the O ORANGE points. The black lines indicate the standard deviation of each point from their average.

Using the averages of the three points that define the second peaks depending on the exercise that we have already studied in the previous sections, we plotted the average second peaks for the four exercises maintaining 102 as the level of the force:

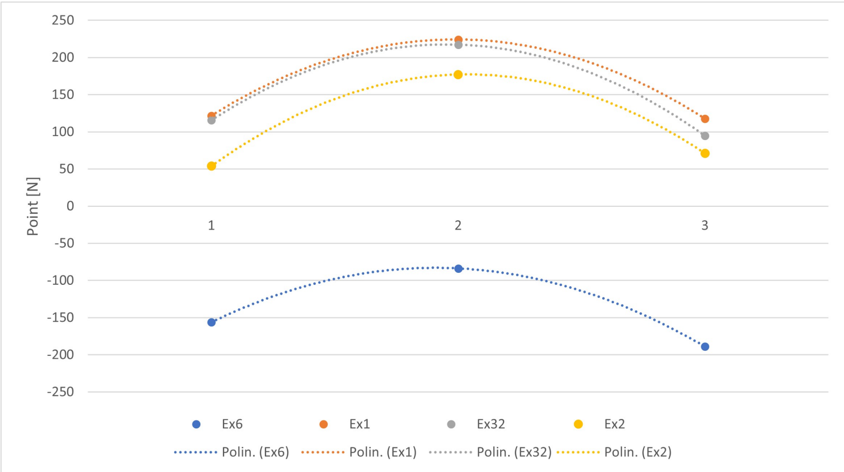

Figure 3.97: In blue the average second peak of the Ground Reaction Force for Single leg squat (Ex6), in orange the average second peak of the Ground Reaction Force for the Normal stance squat (Ex1), in grey the average second peak of the Ground Reaction Force for the Wide stance squat (Ex32), and in yellow the average second peak of the Ground Reaction Force for the Deadlift (Ex2).

We obtained that the Wide stance squat (Ex32), Normal stance squat (Ex1), and Deadlift (Ex2) average second peaks are higher than the Single leg squat (Ex6) average peak. The second peaks for the Single leg squat are at the end of the extension, instead, for the other exercise the second peaks are at the end of the flexion, and for this reason the curve for the Single leg squat is in the negative interval of values.

From here, we calculated the standard deviation between the different curves with respect to the three points and the average of the standard deviation for each of the points:

Ex6-Ex1 [N]	Ex6-Ex32 [N]	Ex6-Ex2 [N]	Ex32-Ex1 [N]	Ex1-Ex2 [N]	Ex32-Ex2 [N]
158,00	152,23	141,83	19,67	59,16	58,07

Table 3.16: The first column considers the standard deviation between the Single leg squat (Ex6) and the Normal stance squat (Ex1). The second column considers the standard deviation between the Single leg squat (Ex6) and Wide stance squat (Ex32). The third column considers the standard deviation between the Single leg squat (Ex6) and Deadlift (Ex2). The fourth column considers the standard deviation between the Wide stance squat (Ex32) and Normal stance squat (Ex1). The fifth column considers the standard deviation between the Normal stance squat (Ex1) and Deadlift (Ex2). The sixth column considers the standard deviation between the Wide stance squat (Ex32) and Deadlift (Ex2).

As we expected, the higher deviation is between the Single leg squat and the others. Instead, the other deviations are very similar and quite small.

Another important parameter to take into consideration is the height in terms of the Ground Reaction Force of the first peak, indicated by the x RED point. This peak is at the end of the extension for the Ex6 and at the and of the flexion for the other exercises. Here are reported the x RED evolution:

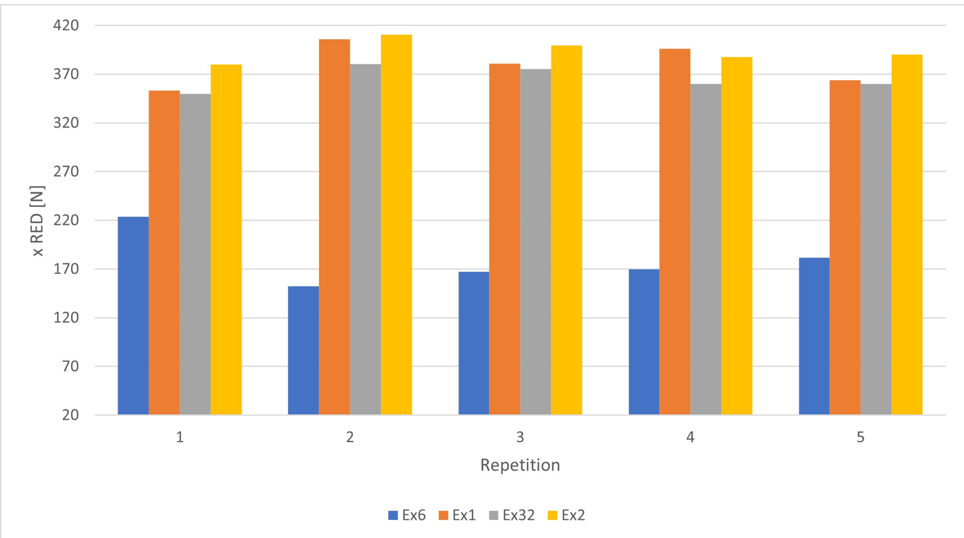

Figure 3.98: In blue the x RED peak for the Single leg squat (Ex6), in orange the x RED peak for the Normal stance squat (Ex1), in grey the x RED peak for the Wide stance squat (Ex32), and in yellow the x RED peak for the Deadlift (Ex2).

As we expected the values of the x RED for the Single leg squat are lower than the others, and we can see that with the Deadlift we obtain higher values of first peaks.

3.5.3. 103 level force

In order to obtain a statistical behavior of the second peaks in the Ground Reaction Force, we calculated the average of the points that identified the curve and obtained the standard deviation between the four different exercises. With this approach, we can evaluate how the Ground Reaction Force changes having the same level of force at the level of the trapezius muscle but facing different exercises.

We have already reported the average and the standard deviation of each point that identifies the second peak for each exercise and level of force 3.4.2 - 3.3.2 - 3.1.2 - 3.2.2. Here we want to visualize the evolution of the point values with respect to the different exercises and maintaining as 102 is the level of force.

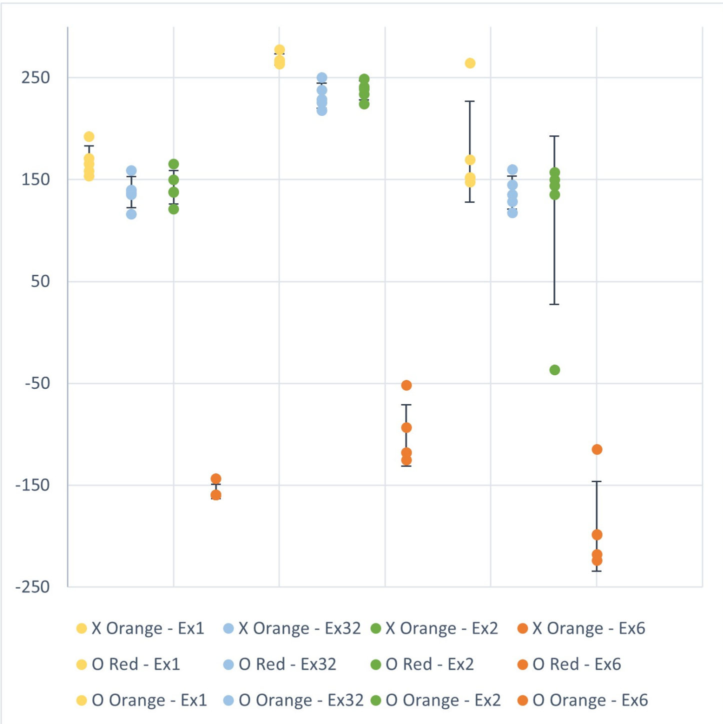

Figure 3.99: The graph reports in yellow the points obtained from the Normal stance squat exercise, in blue the points from the Wide stance squat exercise, in green the points from the Deadlift exercise and in orange the points from the Single leg squat exercise. The first column represents the O RED points, the second column represents the X ORANGE points and the third column represents the O ORANGE points. The black lines indicate the standard deviation of each point from their average.

Using the averages of the three points that define the second peaks depending on the exercise that we have already studied in the previous sections, we plotted the average second peaks for the four exercises maintaining 103 as the level of the force:

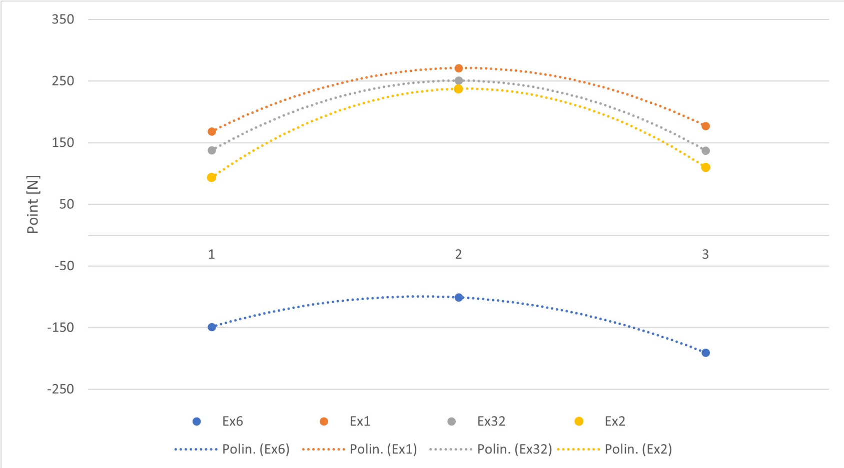

Figure 3.100: In blue the average second peak of the Ground Reaction Force for Single leg squat (Ex6), in orange the average second peak of the Ground Reaction Force for the Normal stance squat (Ex1), in grey the average second peak of the Ground Reaction Force for the Wide stance squat (Ex32), and in yellow the average second peak of the Ground Reaction Force for the Deadlift (Ex2).

We obtained that the Wide stance squat (Ex32), Normal stance squat (Ex1), and Deadlift (Ex2) average second peaks are higher than the Single leg squat (Ex6) average peak. The second peaks for the Single leg squat are at the end of the extension, instead, for the other exercise the second peaks are at the end of the flexion, and for this reason the curve for the Single leg squat is in the negative interval of values.

From here, we calculated the standard deviation between the different curves with respect to the three points and the average of the standard deviation for each of the points:

Ex6-Ex1 [N]	**Ex6-Ex32 [N]**	**Ex6-Ex2 [N]**	**Ex32-Ex1 [N]**	**Ex1-Ex2 [N]**	**Ex32-Ex2 [N]**
188,00	172,40	169,09	61,22	59,77	61,22

Table 3.17: The first column considers the standard deviation between the Single leg squat (Ex6) and the Normal stance squat (Ex1). The second column considers the standard deviation between the Single leg squat (Ex6) and Wide stance squat (Ex32). The third column considers the standard deviation between the Single leg squat (Ex6) and Deadlift (Ex2). The fourth column considers the standard deviation between the Wide stance squat (Ex32) and Normal stance squat (Ex1). The fifth column considers the standard deviation between the Normal stance squat (Ex1) and Deadlift (Ex2). The sixth column considers the standard deviation between the Wide stance squat (Ex32) and Deadlift (Ex2).

As we expected, the higher deviation is between the Single leg squat and the others. Instead, the other deviations are very similar and quite small.

Another important parameter to take into consideration is the height in terms of the Ground Reaction Force of the first peak, indicated by the x RED point. This peak is at the end of the extension for the Ex6 and at the and of the flexion for the other exercises. Here are reported the x RED evolution:

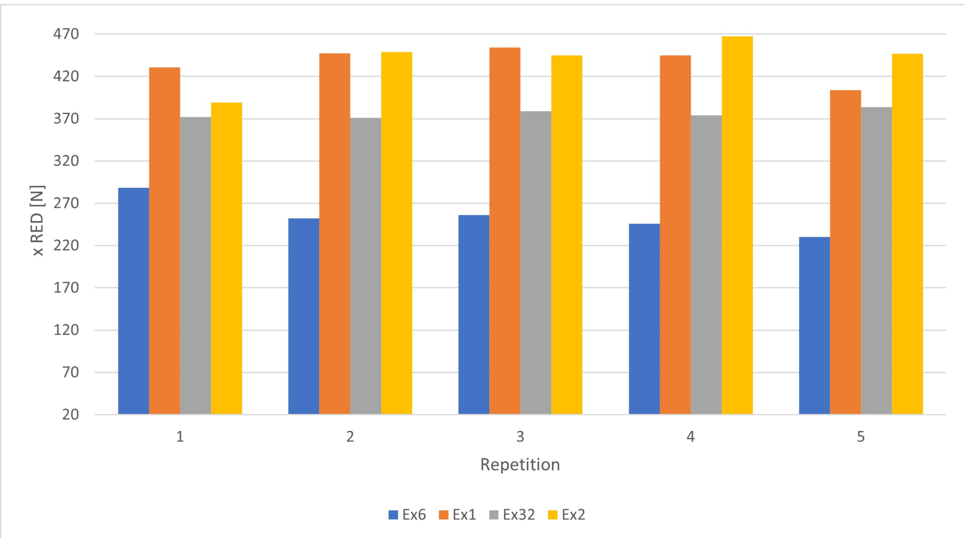

Figure 3.101: In blue the x RED peak for the Single leg squat (Ex6), in orange the x RED peak for the Normal stance squat (Ex1), in grey the x RED peak for the Wide stance squat (Ex32), and in yellow the x RED peak for the Deadlift (Ex2).

As we expected the values of the x RED for the Single leg squat are lower than the others, and we can see that with the Deadlift we obtain higher values of first peaks.

4 | Conclusion and future works

The goal of the thesis is to find out the correlation between the Ground Reaction Force and the different exercises with respect the different level of force. First of all, we want to have a review of the main abbreviations used and what the Results and Discussion chapter showed.

The table below reports the identification name for each exercise used in the NASA protocol.

Exercise	Code
Single leg squat	**EXID-6**
Normal stance squat	**EXID-1**
Wide stance squat	**EXID-32**
Deadlift	**EXID-2**

Table 4.1: The first column reports the four exercises and the second column reports the code identification.

The table below reports the identification code for the three levels of force applied to the trapezius muscle.

Force [lb]	Force [N]	Code
50	222	**101**
60	267	**102**
70	311	**103**

Table 4.2: The first column reports the force in pounds, the second column reports the force in Newton and the first column represents the code identification.

We need to hand up a few steps in order to study the evolution of the Ground Reaction

Force. The signal from the data was characterized by noise; for this, we implemented a code on Phyton to figure out a good signal where it was possible to identify four main points. While knee flexion exists, the Ground Reaction Force decreases until a minimum point, identified as o RED, such as the minimum peak after the maximum peak (x RED). Between the flexion and extension movement, we can consider a second peak (identified with the x ORANGE point) due to the inertial force and co-contraction of the muscles.

During the study, we focus on the second peak, the small one designed by o RED, x ORANGE, and o ORANGE points. We thought that, in general, with a higher force, the second peaks should be higher than the ones with a lower force. So, we could expect that the second peak for the exercise with 103 level of force should be higher than the other two, and the second peak for the exercise with 102 level of force should be higher than the ones with 101 level of force, considering the same exercise. It is what happen for the Normal stance squat, Wide stance squat and Deadlift. Regarding the Single leg squat, the values of the second peaks are negative, it means that the exercise with 101 level of force is higher than the other two, and the second peak for the exercise with 102 level of force is higher than the ones with 103 level of force.

In order to obtain a statistical behaviour of the second peaks in the Ground Reaction Force, we calculated the average of the points that identified the curve and obtained the standard deviation between the three levels of force. With this approach, we can evaluate how the Ground Reaction Force changes facing the same exercise but having different forces at the level of the trapezius muscle. To visualize better the evolution of the average point values that identify the second peak, we plotted the following graph:

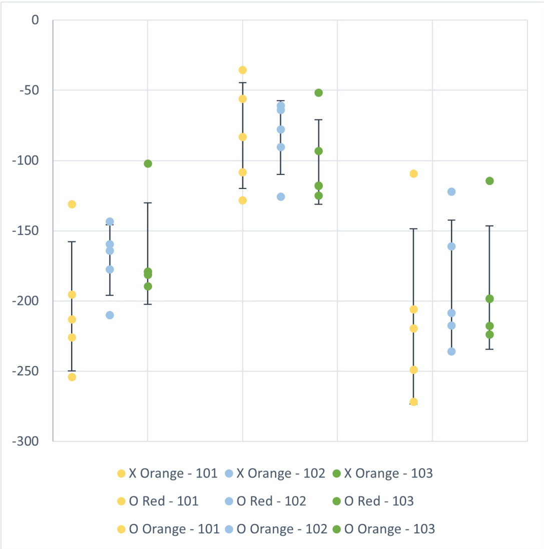

Figure 4.1: Single leg squat

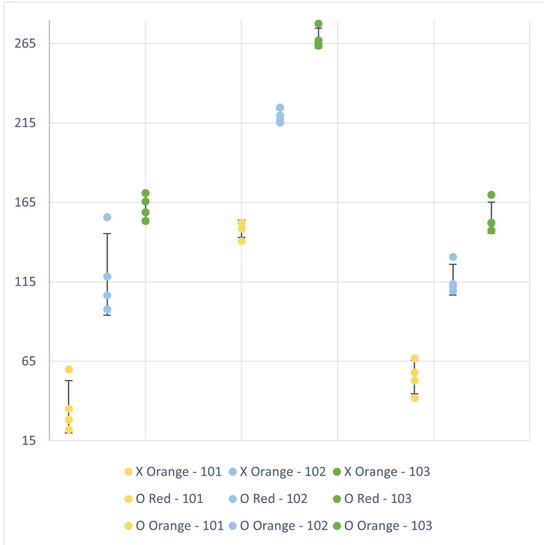

Figure 4.2: Normal stance squat

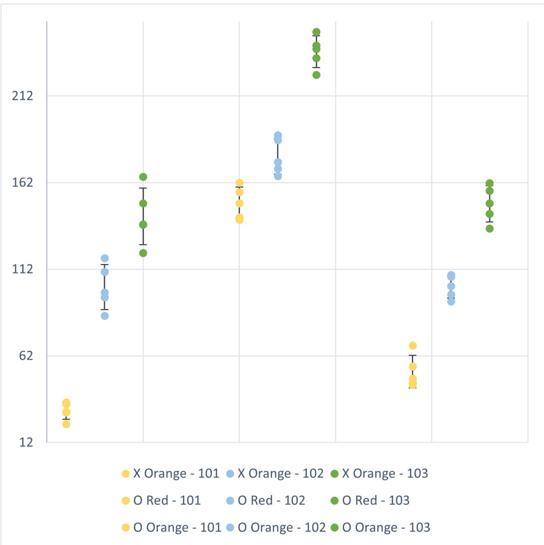

Figure 4.3: Wide stance squat

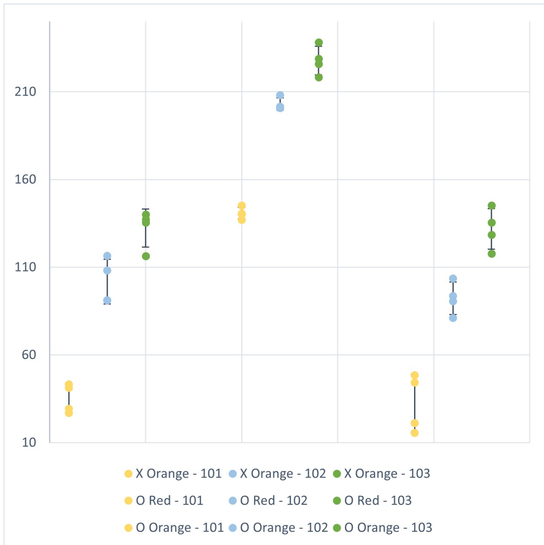

Figure 4.4: Deadlift

Figure 4.5: The graph reports in yellow the points obtained from the exercise with 101 level of force, in blue the points from the 102 level of force and in green the points from the 103 level of force. The first column represents the O RED points, the second column represents the X ORANGE points and the third column represents the O ORANGE points. The black lines indicate the standard deviation of each point from their average.

With the calculation of the standard deviation, we obtained that the higher deviation is between the exercise with 101 force and the one with 103 force, since there is a higher difference in force for all four exercises.

101-102 [N]	101-103 [N]	102-103 [N]
40,87	43,11	33,38

Table 4.3: Single leg squat

101-102 [N]	101-103 [N]	102-103 [N]
40,36	62,37	26,03

Table 4.4: Normal stance squat

101-102 [N]	101-103 [N]	102-103 [N]
34,88	51,39	19,09

Table 4.5: Wide stance squat

101-102 [N]	101-103 [N]	102-103 [N]
27,55	52,98	28,42

Table 4.6: Deadlift

Table 4.7: The first row considers the standard deviation between the exercises with 101 and 102 force. The second row considers the standard deviation between the exercises with 101 and 103 force. The third row considers the standard deviation between the exercises with 102 and 103 force.

We can consider that the standard deviations for the Single leg squat are not so different between each other, with respect to the other exercise. It could mean that the benefits of the Single leg squat don't change a lot changing the level of force.

We did the same comparison maintaining the same level of force and checking between the different exercises:

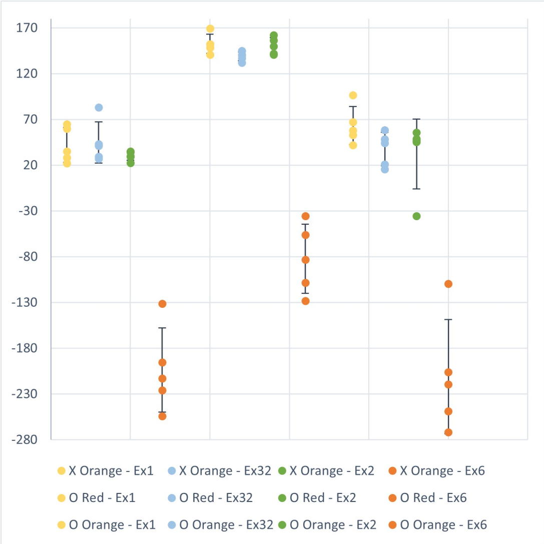

Figure 4.6: 101 level of force

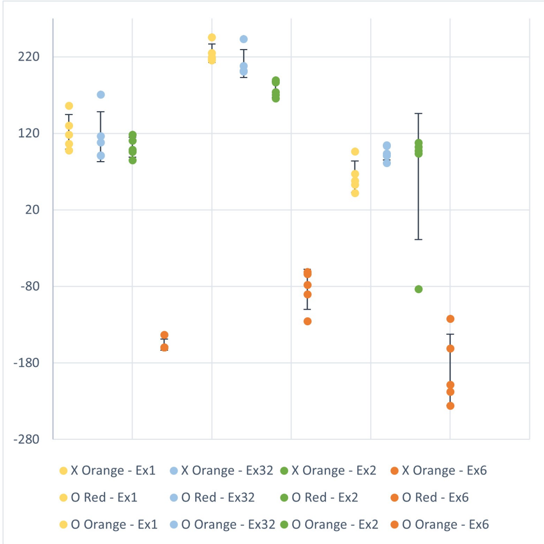

Figure 4.7: 102 level of force

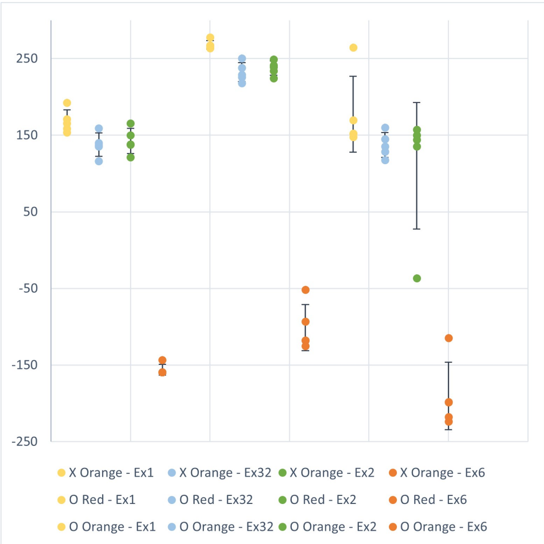

Figure 4.8: 103 level of force

Figure 4.9: The graph reports in yellow the points obtained from the Normal stance squat exercise, in blue the points from the Wide stance squat exercise, in green the points from the Deadlift exercise and in orange the points from the Single leg squat exercise. The first column represents the O RED points, the second column represents the X ORANGE points and the third column represents the O ORANGE points. The black lines indicate the standard deviation of each point from their average.

As result, the higher deviation is between the Single leg squat and the others. This is why the type of exercise is completely different with the others since it uses one leg and not both. Instead, the other deviations are very similar and quite small.

Ex6-Ex1 [N]	Ex6-Ex32 [N]	Ex6-Ex2 [N]	Ex32-Ex1 [N]	Ex1-Ex2 [N]	Ex32-Ex2 [N]
136.20	133.08	128.62	21.34	21.59	24.91

Table 4.8: 101 level of force

Ex6-Ex1 [N]	Ex6-Ex32 [N]	Ex6-Ex2 [N]	Ex32-Ex1 [N]	Ex1-Ex2 [N]	Ex32-Ex2 [N]
158.00	152.23	141.83	19.67	59.16	58.07

Table 4.9: 102 level of force

Ex6-Ex1 [N]	Ex6-Ex32 [N]	Ex6-Ex2 [N]	Ex32-Ex1 [N]	Ex1-Ex2 [N]	Ex32-Ex2 [N]
188.00	172.40	169.09	61.22	59.77	61.22

Table 4.10: 103 level of force

Table 4.11: The first column considers the standard deviation between the Single leg squat (Ex6) and the Normal stance squat (Ex1). The second column considers the standard deviation between the Single leg squat (Ex6) and Wide stance squat (Ex32). The third column considers the standard deviation between the Single leg squat (Ex6) and Deadlift (Ex2). The fourth column considers the standard deviation between the Wide stance squat (Ex32) and Normal stance squat (Ex1). The fifth column considers the standard deviation between the Normal stance squat (Ex1) and Deadlift (Ex2). The sixth column considers the standard deviation between the Wide stance squat (Ex32) and Deadlift (Ex2).

As future work, we would like to compare these data on the ground with data on the ISS. First of all, we would evaluate how change the Ground Reaction Force and the correlation between the three level of force based on the same exercise and the four exercises based on the same level of force with the data on the ISS. Then, we would compare these last results with the one obtained in this study. We would like to suggest to be focus just on the correlation between the Ground Reaction Force with the Bar Height, since the other parameters didn't say a lot on the differences of the exercise.

Bibliography

[1] A. R. Amir, G. Baroni, A. Pedrocchi, D. J. Newman, G. Ferrigno, and A. Pedotti. Measuring astronaut performance on the iss: advanced kinematic and kinetic instrumentation. *IEEE Transactions on Instrumentation and Measurement*, 50(5): 1450–1455, 2001.

[2] J. S. Center. Advanced resistive exercise device (ared) man-in-the-loop test (milt). 2006.

[3] M. A. DiMattia, A. L. Livengood, T. L. Uhl, C. G. Mattacola, and T. R. Malone. What are the validity of the single-leg-squat test and its relationship to hip-abduction strength? *Journal of Sport Rehabilitation*, 14(2):108–123, 2005.

[4] A. A. Ferrando, H. W. Lane, C. A. Stuart, J. Davis-Street, and R. R. Wolfe. Prolonged bed rest decreases skeletal muscle and whole body protein synthesis. *American Journal of Physiology-Endocrinology and Metabolism*, 270(4):E627–E633, 1996.

[5] M. Heer and W. H. Paloski. Space motion sickness: incidence, etiology, and countermeasures. *Autonomic Neuroscience*, 129(1-2):77–79, 2006.

[6] E. Kerstman and R. Scheuring. Nasa musculoskeletal space medicine and reconditioning program. In *83rd AsMA Annual Scientific Meeting*, number JSC-CN-24943, 2011.

[7] S. Lee, K. Cobb, J. A. Loehr, D. Nguyen, and S. M. Schneider. Foot-ground reaction force during resistive exercise in parabolic flight. *Aviation, space, and environmental medicine*, 75(5):405–412, 2004.

[8] C. Lloyd. Mission x: Train like an astronaut. international fitness challenge. Technical report, 2011.

[9] S. Lorenzetti, M. Ostermann, F. Zeidler, P. Zimmer, L. Jentsch, R. List, W. R. Taylor, and F. Schellenberg. How to squat? effects of various stance widths, foot placement angles and level of experience on knee, hip and trunk motion and loading. *BMC Sports Science, Medicine and Rehabilitation*, 10(1):1–11, 2018.

[10] A. D. Moore Jr, J. S. Center, and M. F. McCleary. Evaluation of maximal oxygen uptake and submaximal estimates of vo2max before, during, and after long duration international space station missions.

[11] G. D. Myer, A. M. Kushner, J. L. Brent, B. J. Schoenfeld, J. Hugentobler, R. S. Lloyd, A. Vermeil, D. A. Chu, J. Harbin, and S. M. McGill. The back squat: A proposed assessment of functional deficits and technical factors that limit performance. *Strength and conditioning journal*, 36(6):4, 2014.

[12] G. Neri, G. Mascetti, and V. Zolesi. Elite s2–a facility for quantitative human movement analysis on board the iss. *Microgravity Science and Technology*, 26:271–278, 2014.

[13] M. Pantak. Ground reaction forces generated during rhythmical squats as a dynamic loads of the structure. In *IOP Conference Series: Materials Science and Engineering*, volume 245, page 022053. IOP Publishing, 2017.

[14] N. Petersen, P. Jaekel, A. Rosenberger, T. Weber, J. Scott, F. Castrucci, G. Lambrecht, L. Ploutz-Snyder, V. Damann, I. Kozlovskaya, et al. Exercise in space: the european space agency approach to in-flight exercise countermeasures for long-duration missions on iss. *Extreme physiology & medicine*, 5(1):1–13, 2016.

[15] S. Siceloff. Colbert ready for serious exercise. *National Aeronautics and Space Administration*, 2009.

[16] W. K. Thompson, C. A. Gallo, L. Crentsil, B. E. Lewandowski, B. T. Humphreys, J. K. DeWitt, R. S. Fincke, and L. Mulugeta. Digital astronaut project biomechanical models: Biomechanical modeling of squat, single-leg squat and heel raise exercises on the hybrid ultimate lifting kit (hulk). Technical report, 2015.

[17] W. K. Thompson, C. A. Gallo, B. T. Humphreys, A. P. Godfrey, K. M. Jagodnik, J. K. Dewitt, and B. E. Lewandowski. Effect of loading configuration on kinematics and kinetics for deadlift and squat exercises: Case study in modeling exercise countermeasure device for astronauts. Technical report, 2019.

[18] L. Vecchio, H. Daewoud, and S. Green. The health and performance benefits of the squat, deadlift. *and bench press. MOJ Yoga Phys. Ther*, 3:40–47, 2018.

List of Figures

List of Tables

List of Symbols

The table below reports the identification name for each exercise used in the NASA protocol.

Exercise	Code
Single leg squat	**EXID-6**
Normal stance squat	**EXID-1**
Wide stance squat	**EXID-32**
Deadlift	**EXID-2**

Table 4.12: The first column reports the four exercises and the second column reports the code identification.

The table below reports the identification code for the three levels of force applied to the trapezius muscle.

Force [lb]	Force [N]	Code
50	222	**101**
60	267	**102**
70	311	**103**

Table 4.13: The first column reports the force in pounds, the second column reports the force in Newton and the first column represents the code identification.

Ringraziamenti

Dedico questa tesi ai miei genitori, solo grazie ai loro sacrifici sono la persona che sono. Grazie ad ogni singolo momento insieme, ai momenti che mi avete lasciato vivere lontano da casa, alla libertà che mi avete sempre dato, anche la libertà di sbagliare, al supporto in questi cinque anni. Senza il vostro sostegno, oggi non sarei un ingegnere.

Grazie a te, mamma. Tu che ci hai sempre creduto, la prima a crederci e all'inizio anche l'unica che ci credeva. Anche da lontano sei sempre stata la prima a supportarmi e sopportarmi, in qualsiasi momento e per qualsiasi occasione. La tua forza è invidiabile e spero di avere preso il tuo stesso coraggio di mettermi in gioco ogni giorno.

A te, babbo, così silenzioso nel tuo modo di esserci, ma ora so che i tuoi abbracci e sguardi quando ritorno o parto da casa valgono più di mille parole. Forse non ti aspettavi tutte le soddisfazioni di questi anni, ma vederti stupito ogni volta mi fa orgoglio.

Ogni singola parola di questa tesi l'ho scritta pensando a voi, seduta alla mia scrivania di ESA, guardando le bandiere dei vari paesi del mondo e con musica malinconica nelle cuffie. Non potrei mai descrivere a parole la forza che mi avete dato.

A mio fratello, noi siamo sempre stati il classico cane e gatto, così diversi ma così simili. Questo traguardo è anche merito tuo, grazie ad avermi sempre spronato ad aprire gli occhi sugli argomenti più svariati.

A mia nonna Luida, ogni giorno stupisci con la forza che ancora hai. Sei un esempio di vita.

A tutta la mia famiglia che mi aspetta a braccia aperte ogni volta che ritorno a casa.

A Riccardo, che ogni giorno mi rende orgogliosa della persona che è. Anche se non te ne rendi conto, sei una delle persone più forti che abbia mai conosciuto. Quello che ti distingue è la tua forza di volontà davanti a tutto e tutti. Mi rende orgogliosa vederti anche fragile e di poter stare accanto a te. Con te si è creato un rapporto che va oltre a fiori e cioccolatini, sappiamo entrambi che per qualsiasi momento della vita, bello o brutto che sia, ci saremo l'uno per l'altro.

Grazie alla famiglia di Riccardo, che fin da subito mi ha fatto sentire parte di loro.

Alle persone che ci sono sin dal primo giorno, Antonella, Valentina e Francesca. Milano è diventata casa grazie a voi. Vederci crescere insieme è stato un onore, vederci costruire le nostre strade è motivo di orgoglio. È vero che da soli non si può andare lontani, e io solo grazie a voi ho cercato di dare sempre il mio meglio in questi anni.

Alle persone che ho conosciuto durante il tragitto, fondamentali per affrontare le sfide che l'università ogni giorno ci mette davanti.

A PoliSpace e a tutte le persone che ne fanno e ne hanno fatto parte. Entrare in associazione mi ha fatto capire tanto di me e soprattutto quello che veramente mi piaceva. Non smetterò mai di dire l'importanza di fare esperienze al di fuori dei corsi universitari. PoliSpace mi ha portato a raggiungere uno degli obiettivi più importanti della mia vita e di questo ne sarò per sempre grata. Grazie a Dario e Maddalena, per il sostegno che ci siamo sempre dati e gli infiniti gossip.

Grazie alle esperienze all'estero in questi anni.

Partendo dall'Erasmus che mi ha fatto veramente iniziare a credere in me stessa e mi ha fatto conoscere "i ragazzi di Brescia" che porterò sempre nel cuore.

Grazie ad ESA e alle persone meravigliose che ho conosciuto. Gli ultimi mesi della magistrale sono stati meravigliosi grazie a voi. Prima di cominciare l'internship pensavo che l'esperienza sarebbe stata fantastica per l'ambiente lavorativo, ma quello che ha fatto veramente la differenza sono i ragazzi che ci lavorano. Non posso non ringraziare David, colui che ha avuto la pazza idea di scegliermi, e Nolan che mi ha seguita per tutti questi mesi. Grazie a tutti gli interns che hanno condiviso con me questi mesi, grazie per il sostegno reciproco e per avermi fatto conoscere mille altre cose. Siete stati fondamentali per le mie scelte ed è stato incredibile vedere come persone da tutto il mondo e con diversi percorsi si intrecciassero così bene. Grazie a Nadia, Jacopo, Denzel, Magda, Preve, Pablo, Danny, Giorgio, Daniel, Lucia e tante altre persone per aver condiviso con me i vostri sogni.

Grazie a casa, Carrara, che sempre è nel mio cuore. Grazie per farmi respirare aria pulita ogni volta che ritorno. Grazie alle persone che definisco ancora casa come Carolina e Benedetta dopo tutto questo tempo. Ritornare è sempre bello.

Ad ogni treno, aereo, bus che ho preso in questi anni che mi hanno fatto arrivare in qualsiasi parte del mondo. A tutte le volte che mi sono emozionata davanti a un finestrino per una nuova partenza, per una nuova avventura. A tutte le volte che quei mezzi mi hanno riportato nelle braccia dei miei genitori.

Un pensiero va alle ragazze e ai ragazzi che iniziano o stanno facendo questo tipo di percorso. Nulla è stato facile e nulla è stato regalato, molte volte non ci si sente abbastanza, neanche davanti ad un 30. Purtroppo nella nostra società spesso ci ritroviamo persone che pensano che un voto conti più di chi si ha davanti, vorrei dire che non è così. Ce ne sono altrettante che vi faranno sentire al posto giusto a prescindere dal voto preso, ma da quello che veramente si è. Nella testa ci sarà sempre il conflitto tra faccio quello che gli altri si aspettano che faccia o faccio quello che voglio fare. Fate la seconda, solo essendo noi stessi ci troveremo in posti dove ci sentiremo abbastanza. In questi due anni di magistrale ho dato il massimo per raggiungere quel meraviglioso e così perfetto 110. Bene, me lo sono vista togliere all'ultimo con una cattiveria mai affrontata prima in un esame. Ho preferito accettare ed estendere l'internship in ESA che pensare che io non fossi abbastanza per il voto che avrei voluto. Le esperienze fanno le persone e io sono orgogliosa di tutto quello che ho portato a casa in questi anni e un voto non mi farà cambiare idea.

Vorrei dare un bacio sulla fronte alla piccola Elisabetta al suo primo giorno di università, come fece mio babbo con gli occhi lucidi, e dirle che andrà tutto bene.

Non vedo l'ora di vedere e vivere tutte le future avventure.

Grazie.

Acknowledgements

I dedicate this thesis to my parents; only thanks to their sacrifices am I the person I am today. Gratitude for every single moment together, for the times you let me live away from home, for the freedom you always granted me, even the freedom to make mistakes, and for the support over these five years. Without your support, I wouldn't be an engineer today.

Thank you, mom. You always believed, the first and initially the only one who believed on me. Even from afar, you've always been the first to support and endure me, at any time and for any occasion. Your strength is admirable, and I hope I have inherited your courage to face each day.

To you, Dad, so silent in your way of being there, but now I know that your hugs and glances when I return or leave home are worth more than a thousand words. Perhaps you didn't expect all the achievements of these years, but seeing you surprised every time makes me proud.

Every single word of this thesis was written thinking of you, sitting at my desk at ESA, looking at the flags of various countries around the world and listening to melancholic music. I could never put into words the strength you've given me.

To my brother, we have always been the classic 'cane e gatto', so different yet so similar. This achievement is also thanks to you, for always pushing me to open my eyes to the most diverse topics.

To my grandmother Luida, you amaze every day with the strength you still have. You are an example of life.

To my entire family waiting with open arms every time I return home.

To Riccardo, who makes me proud every day of the person he is. Even if you don't realize it, you are one of the strongest person I have ever met. Your distinguishing feature is your willpower in the face of everything and everyone. I am proud to see you even vulnerable and to be able to stand by you. With you, a relationship has been created that goes beyond flowers and chocolates; we both know that for any moment in life, good or bad, we will be there for each other.

Thanks to Riccardo's family, which immediately made me feel part of them.

To the people who have been there since day one, Antonella, Valentina, and Francesca. Milan has become home thanks to you. Watching us grow together has been an honor, seeing us build our paths is a source of pride. It is true that we cannot go far alone, and only thanks to you have I tried to always give my best in these years.

To the people I met along the way, crucial to facing the challenges that university puts before us every day.

To PoliSpace and all the people who are and have been part of it. Joining the association made me understand a lot about myself and, above all, what I really liked. I will never stop emphasizing the importance of gaining experiences outside of university courses. PoliSpace has led me to achieve one of the most important goals of my life, and I will be forever grateful for that. Thanks to Dario and Maddalena for the support we have always given each other and the endless gossip.

Thanks to the experiences abroad in these years, starting with Erasmus, which really made me start believing in myself and introduced me to "the guys from Brescia" who I will always carry in my heart.

Thanks to ESA and the wonderful people I met. The last months of the master's degree were wonderful thanks to you. Before starting the internship, I thought the experience would be fantastic for the working environment, but what really made the difference was the people working there. I cannot but thank David, the one who had the crazy idea of choosing me, and Nolan, who followed me for all these months. Thanks to all the interns who shared these months with me, thanks for the mutual support and for making me discover a thousand other things. You have been fundamental for my choices, and it was incredible to see how people from all over the world and with different paths intertwined so well. Thanks to Nadia, Jacopo, Denzel, Magda, Preve, Pablo, Danny, Giorgio, Daniel, Lucia, and many other people for sharing your dreams with me.

Thanks to home, Carrara, always in my heart. Thanks for letting me breathe clean air every time I come back. Thanks to the people I still define as home, like Carolina and Benedetta after all this time. Returning is always beautiful.

To every train, plane, bus I took in these years that took me anywhere in the world. To every time I got emotional in front of a window for a new departure, for a new adventure. Every time those means brought me back into the arms of my parents.

A thought goes to the girls and boys who are starting or are on this kind of path. Nothing has been easy, and nothing has been given, many times you don't feel good enough, not even in front of a 30. Unfortunately, in our society, we often find people who think that a grade matters more than who is in front of them. I would like to say that it is not so. There are just as many who will make you feel in the right place regardless of the grade you get, but based on who you really are. In our minds, there will always be a conflict between doing what others expect us to do or doing what we want to do. Choose the latter, only by being ourselves will we find ourselves in places where we will feel good enough. In these two years of the master's degree, I did my best to reach that wonderful and so perfect 110. Well, I saw it taken away at the last moment with a cruelty never faced before in an exam. I preferred to accept and extend the internship at ESA rather than think that I was not good enough for the grade I would have received. Experiences make people, and I am proud of everything I have brought home in these years, and a grade will not change my mind.

I would like to give a kiss on the forehead to little Elisabetta on her first day of university, as my father did with teary eyes, and tell her that everything will be fine.

I can't wait to see and live all the future adventures.

Thank you.