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SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

EXECUTIVE SUMMARY OF THE THESIS

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

LAUREA MAGISTRALE IN BIOMEDICAL ENGINEERING - INGEGNERIA BIOMEDICA

**Author:** ELISABETTA MARRUCCI

**Advisor:** PROF. GIANCARLO FERRIGNO

**Co-advisor:** PROF. MANUELA GALLI

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## 1. Introduction

ARED-Kinematics plans on improving the subject specific effectiveness of daily exercises on the International Space Station (ISS) by estimating internal body loads; studying how kinematic data 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 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. For clarification, here are reported the codes to identify the name of the exercises and the levels of force used in the NASA protocol:

- Single leg squat: Ex.6
- Normal stance squat: Ex.1
- Wide stance squat: Ex.32
- Deadlift: Ex.2
- Force level 101: 222 N
- Force level 102: 267 N
- Force level 103: 311 N

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?".

## 2. Materials and Methods

The whole project consists of obtaining some parameters during the performance of the exercises from a subject on the ground. Here are indicated the parameters extracted from the experiment:

- Ground Reaction Force
- Rotational Arm Position
- Bar Angle Position
- Center Of Pressure along x and y
- Bar Height

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 ISS. The raw data used in the current work come from the experiment at Johnson Space Center and 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 data filtering, 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 squat's technique. In the case of unprofessionally performed squats, 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. [1]

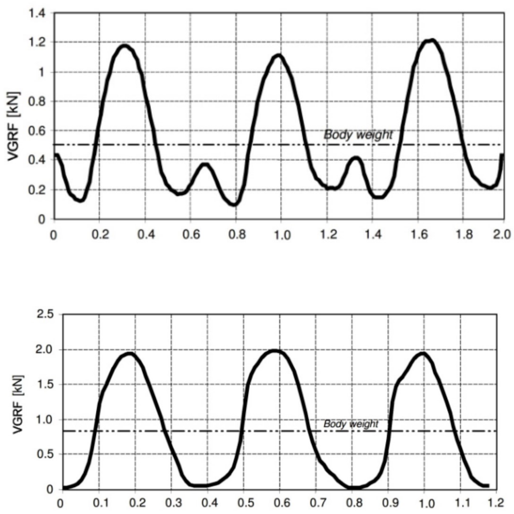


Figure 1: Examples of the Ground Reaction Force generated: the first one, during squats with fully straightened legs at the end of ascending phase of the squat; the second one, during squats with partially straightened legs during ascending phase of the squat.

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. The 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.

In the following graphs, we show 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

## 3. Results and Discussions

Here, we are going to consider the results of the parameters extracted from the sensors exercise by exercise, focusing on the Ground Reaction Force and Bar Height. Along with the presentation of the results, they are combined with a discussion paragraph. There is a strong relationship between the values of the second peaks and the values of the Bar Height. In general, with a higher force, the second peaks should be higher than those 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. Then, 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. This section presents the

Ground Reaction Force and Bar Height curves solely at the 101 force level due to space limitations. Across all exercises, the evolution of these curves remains highly consistent. A comparison is provided to offer a comprehensive view, specifically highlighting the minor peaks across

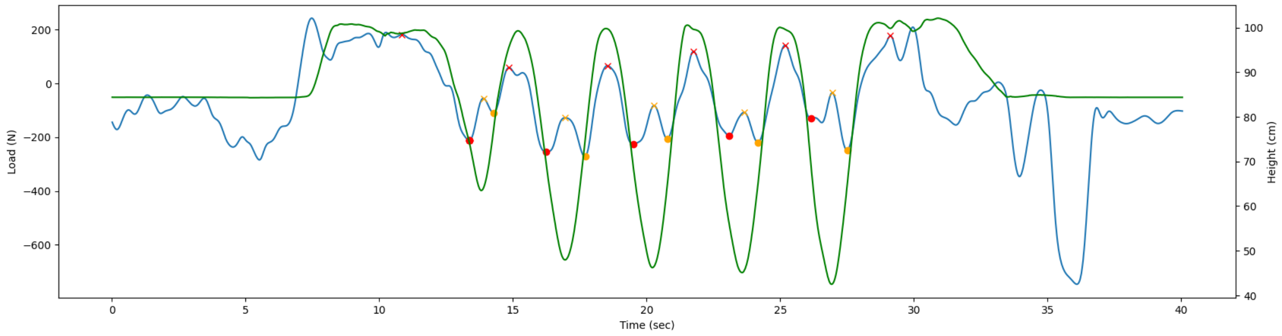


Figure 2: Single leg squat. In blue the evolution of the load with 101 force, in green the evolution of the bar height with 101 force.

varying force levels.

## 3.1. Single leg squat

In Figure 2, the subject starts by standing up, where the Ground Reaction Force 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). Between the flexion and extension movement, we can consider a second peak (x ORANGE point) due to the inertial force and co-contraction of the muscles. In the Single leg squat the small peaks are at the end of the flexions.

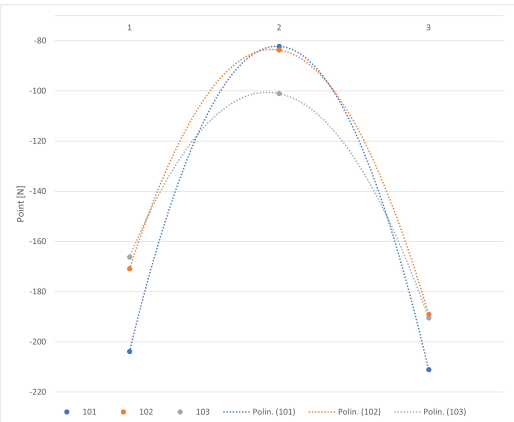


Figure 3: Single leg squat. In blue the average second peak of the Ground Reaction Force with 101 force, in orange the average second peak of the Ground Reaction Force with 102 force, and in grey the average second peak of the Ground Reaction Force with 103 force.

Then, we calculated the average of the three points that identify the small peaks for each 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 (Figure 3).

## 3.2. Normal stance squat

In Figure 5, 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. 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. We are considering the Normal stance squat, where the small peaks are at the end of the extension.

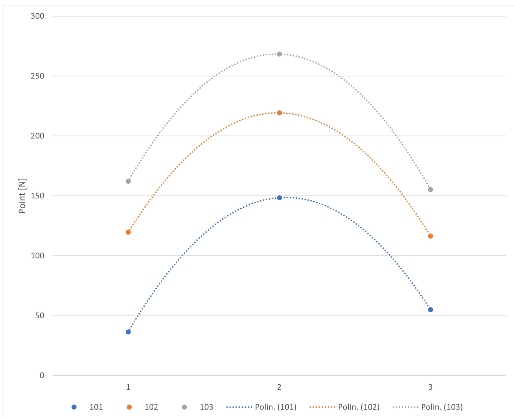


Figure 4: Normal stance squat. In blue the average second peak of the Ground Reaction Force with 101 force, in orange the average second peak of the Ground Reaction Force with 102 force, and in grey the average second peak of the Ground Reaction Force with 103 force.

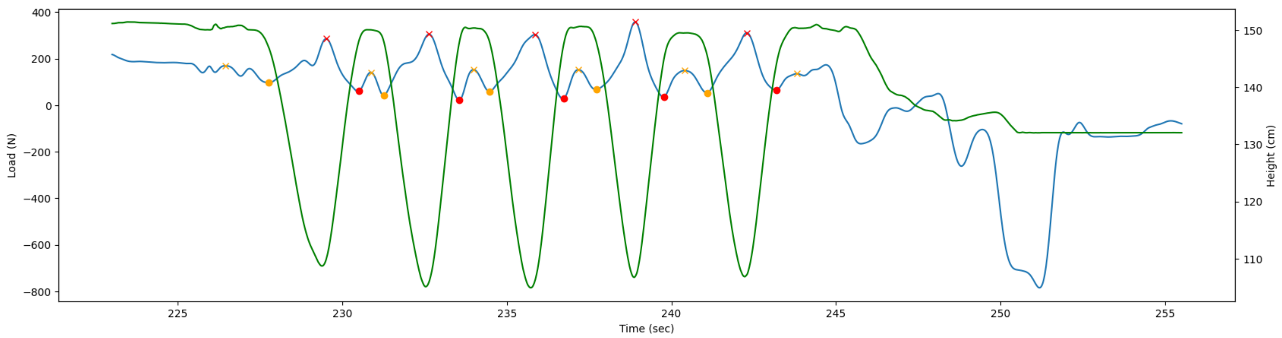


Figure 5: Normal stance squat. In blue the evolution of the load with 101 force, in green the evolution of the bar height with 101 force.

Then, we calculated the average of the three points that identify the small peaks for each level of force. In this exercise, the subject reaches very few different levels of flexions for the different repetitions. Thanks to this quite constant behavior the second peaks are coherent for each repetition. 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 (Figure 4).

## 3.3. Wide stance squat

For the wide stance squat, the relation between the Ground Reaction Force and the Bar Height is the same as for the Normal stance squat (Figure 6). 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. Between the extension and flexion movement, we can consider a second peak. We are considering the Wide stance squat, where the small peaks are at the end of the extension.

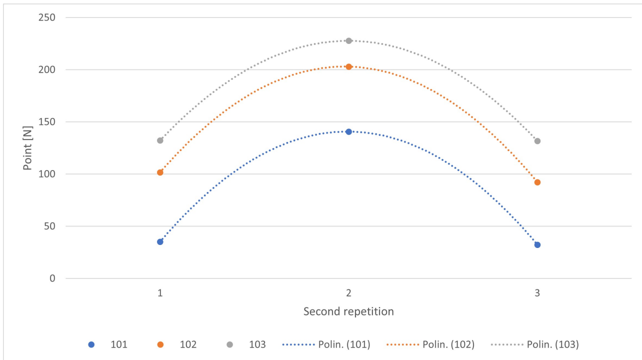


Figure 7: Wide stance squat. In blue the average second peak of the Ground Reaction Force with 101 force, in orange the average second peak of the Ground Reaction Force with 102 force, and in grey the average second peak of the Ground Reaction Force with 103 force.

Then, we calculated the average of the three points that identify the small peaks for each level of force. Also in this case, the second peak for the exercise with 103 level of force should be higher than the other two, and the second peak

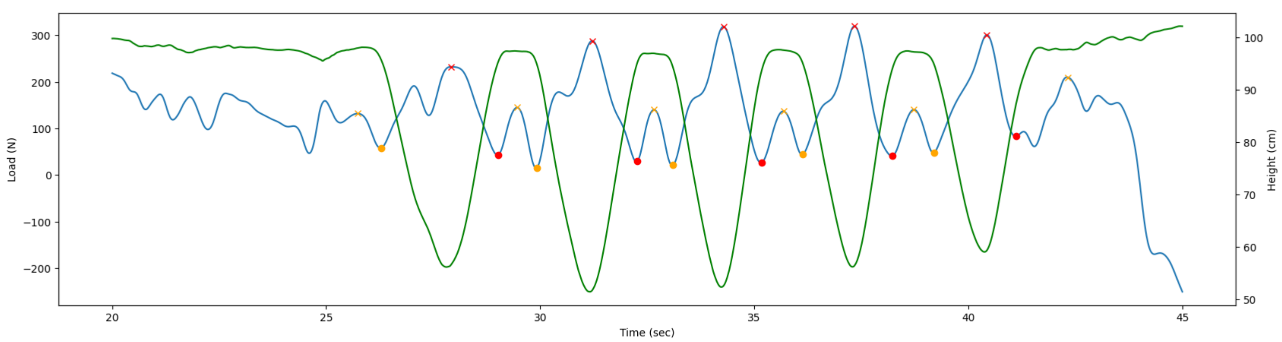


Figure 6: Wide stance squat. In blue the evolution of the load with 101 force, in green the evolution of the bar height with 101 force.

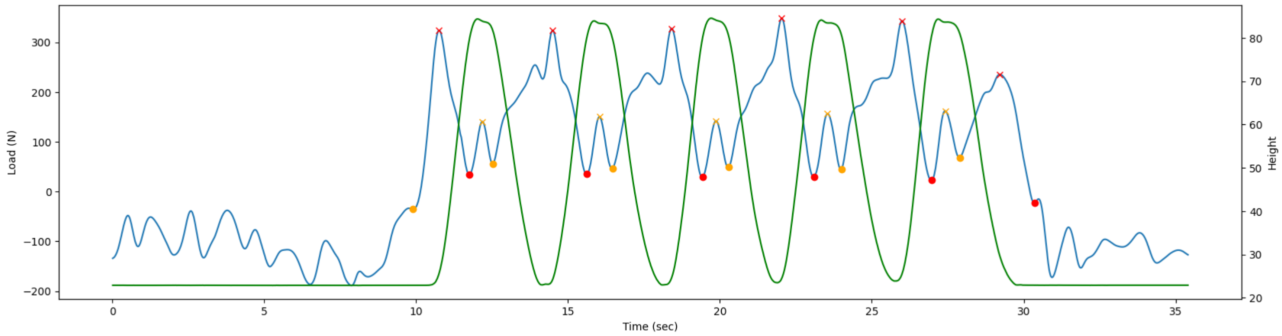


Figure 8: Deadlift. In blue the evolution of the load with 101 force, in green the evolution of the bar height with 101 force.

for the exercise with 102 level of force should be higher than the ones with 101 level of force (Figure 7).

### 3.4. Deadlift

As shown in Figure 8, the subject starts already squatted with their knees flexed, 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. 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. We are considering the Deadlift, where the small peaks are at the end of the extension.

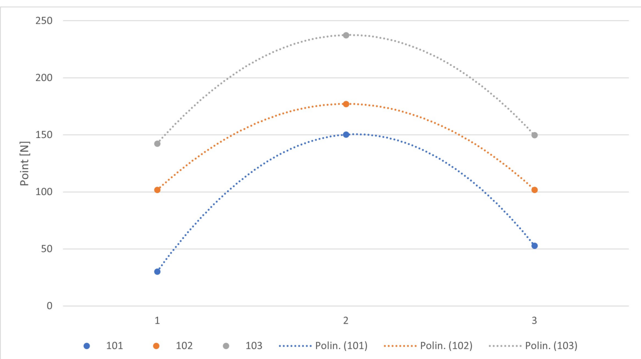


Figure 9: Deadlift. In blue the average second peak of the Ground Reaction Force with 101 force, in orange the average second peak of the Ground Reaction Force with 102 force, and in grey the average second peak of the Ground Reaction Force with 103 force.

Then, we calculated the average of the three points that identify the small peaks for each level of force. Also in this case, 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 (Figure 9).

## 4. Conclusion and future works

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

Table 1: Single leg squat

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

Table 2: Normal stance squat

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

Table 3: Wide stance squat

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

Table 4: Deadlift

Table 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.

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 (Table 5).

| **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 6: 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 7: 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 8: 103 level of force

Table 9: 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).

With the calculation of the standard deviation, we found that there is a higher standard deviation between data points in the 101 Force level and 103 Force level, since there is a higher difference in force for all four exercises.
We did the same comparison maintaining the same level of force and checking between the different exercises. As result, the higher deviation is between the Single leg squat and the other exercises. 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 (Table 9).

For future work, we would like to compare these data on the ground with data on the ISS. First of all, we would evaluate how the Ground Reaction Force changes and the correlation between the three levels of force based on the same exercise. Additionally, we would compare the four exercises based on the same level of force with the data on the ISS. Then, we would compare these last results with those obtained in this study. We suggest focusing on the correlation between Ground Reaction Force with the Bar Height, since other parameters, such as the other parameters differed minimally between exercises.

## References

[1] Marek 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.