Squat biomechanics in weightlifting: foot attitude effects

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Abstract. Squat weight lift is a common exercise in physical training used both in weightlifters specific training and in general athletes for leg force increment. When weight load on subject shoulders is rather heavy as compared with full body weight, gesture biomechanics becomes critical, since injuries may occur when gesture is not controlled or performed in a wrong way. Experienced trainers are aware of such issues and give proper instructions to obtain best performance at a minimum injury risk. In this work a quantitative approach is presented, supported by biomechanical measurements to determine the effects on main articulations of different postures during the exercise. Preliminary results confirm good practices giving a quantitative indication of joints solicitations.

1. Introduction
Squat weight lift is a widely diffused practice in force training programs applied to several sports such as athletics soccer, rugby and, specifically, in Olympic weightlifting. The focus is on upper leg and low back muscle conditioning [1-3]. Specific literature is available in sport related journals, but it is not common to find a quantitative movement description [4-6, 7]. A brief qualitative gesture overview is given hereafter.

Barbell loaded squat movement can be executed with barbell in front or back positions. In the following we are going to consider the most common execution, the high back load squat with barbell positioned upon shoulders, over the acromyon, as showed in Figure 1. The movement starts with the subject in a static upright position. A continuous leg compression, including hip, knee and ankle movements, brings the body in the final position as deep as desired. A rising movement follows with the subject returning in upright position. Different leg compressions are possible, usually distinguished according to the amount of knee flexion, denoted by partial, half or complete squat. In this communication, complete squat with a knee flexion above 100° is considered. Weight lift purpose in training is to develop muscular force and in the literature papers are available that propose the use of EMG to describe muscle activation as a function of gesture parameters such as squat depth. As regards rehabilitation some references focus on the effect on overall squat movement, of low efficiency or low force developed by some specific muscles involved in the movement, or articular mobility problems mainly in the ankle.

During squat weightlift exercise, injuries are possible. Muscular injuries are mainly due to overloads, improper warm up or sudden unbalance. On the other hand, a wrong or un-correct execution of the exercise might procure, during time, injuries involving articulations [8]. These problems are mainly due to the improper loads on the articulations procuring mechanical effects on the compliant elements such as ligaments and cartilages. Papers are available regarding muscle activation studies by surface electromyography in various conditions [9]. On the other hand, as far as we know, a quantitative
approach considering movement deficiencies and improper gesture execution effects on articulations stresses, based upon a set of biomechanical measurements and models is not available in literature, and here we propose a first approach with some preliminary results [10-13]. In particular, we are interested in investigating the effect on articular moments of foot anterior-posterior attitude during the gesture. In fact, it is possible to maintain the load in the middle of the foot sole, or force a frontal loading moving the force toward foot tip, or toward the heel moving the load on the back. Correct gesture procedure requires a median loading, as recommended by athletics trainers, but due to heavy loads and little unbalances it is rather easy to move the load under the foot sole, with consequences on articular load. Besides that, it is interesting to note that specific weightlifting shoes are available [14, 15]. They present a rigid sole to increase foot stability and a few centimeters wedge so that the heel is just a little higher than the foot tip [16]. This seems to be in contrast with the recommended good practice, since the wedge implies the tendency to lead the foot in front, so shoes effect on articular load is worth to be investigated. In the following we will define the experimental protocol, introduce the experimental setup, and final we will present and discuss some preliminary results.

2. Methods

2.1. Experimental protocol
As mentioned in the Introduction, our goal is to understand the effects of foot attitude on joints internal forces, during gesture execution. A protocol has been thus designed, to guarantee repeatability evaluation and reproducibility of the experiment. The test sequence was defined according to table 1, considering the different factors under investigations and controlling subject fatigue during the experiment. A preliminary static measurement is necessary to establish marker placement positions on the subject. Then subject performs the sequence of weightlifting according to table 1, introducing pauses as required.

Table 1. Experimental protocol.

| Load weight [kg] | Test # | Test # | Test # | Test # |
|-----------------|--------|--------|--------|--------|
| 8               | Front  | Middle | 8      | Middle |
| 44              | Rear   | 2      | 8      | Rear   |
| 8               | Middle | 3      | Front  | 9      |
| 44              | Front  | 4      | Middle | 10     |
| 8               | Rear   | 5      | Rear   | 11     |
| 44              | Middle | 6      | Front  | 12     |

2.2. Biomechanical model
A planar biomechanical model has been considered, since we are mainly interested in studying the gesture in the sagittal plane, with a special focus on the anterior posterior direction. In fact, the gesture is almost planar and such approximation is in general good to describe gesture biomechanics unless medio-lateral asymmetries have to be investigated. The model we are considering is schematised in figure 1 with the most important anatomical landmarks describing the movement reported in the table. Eight active markers have been placed on the subjects in such anatomical points. Markers misalignment from the reference sagittal plane is small and during the gesture they move very little out of the plane – less than ± 30 mm. Markers are placed on the subject only since we are interested in subject’s lower limbs biomechanics, and we are considering rear barbell squat only so during the gesture barbell does not move in relation to subject’s arms. Some model parameters can be measured directly on the subjects such as anthropometric segments lengths, while others such as mass anthropometry, centres of mass positions and inertia are derived from standard anthropometric tables such as those reported in [17].
biomechanical model enables inverse kinetics analysis to determine internal forces and moments at the articulation joints, as it will be presented in the next subsection.

![Figure 1. Squat weightlift biomechanical model and markers positions.](image)

| Marker | Position  |
|--------|-----------|
| 1      | acromion  |
| 2      | iliac crest |
| 3      | trochanter |
| 4      | knee      |
| 5      | ankle     |
| 6      | heel      |
| 7      | metatarsus|
| 8      | foot tip  |

2.3. Measurement system

Kinematic measurements are carried out with a video system based on a Dalsa Falcon camera – 1400x1024, 100Hz frame rate, Camera Link connection -. The video system is properly aligned and calibrated with a reference length (1.2 m - 0.1 m steps) placed on the measurement plane the to obtain the sensitivity constant (about 1.4 mm/pixel) and minimise prospective compensations and residual distortions. In these conditions markers movement out of the plane implies a deviation of less than ± 2% in the sensitivity. Acquisition and processing MatLab® code gives as output markers coordinates in the sagittal plane in time. Kinetic measurement are based on two force platforms - P6000 BTS Bioengineering, 600 x 400 mm, 2kN full scale, 1kHz sampling rate -. Data acquisition is managed separately for kinematic and kinetics systems, and they are hardware synchronised.

3. Results

Two subjects – male, 22 years old– underwent the protocol presented in par. 2.1. In order to be able to compare different gesture executions by the same or different subjects it is necessary to introduce a standard gesture cycle [18]. This is for some gestures straightforward, such as in the case of walking or running, for example considering successive heel contacts on the ground. In weightlifting it is a little bit tricky since there is no specific event at execution start or stop. A standard cycle has been defined according to hip position – marker 3 in figure 1: by setting a proper threshold it is possible to identify the initial downward movement and gesture conclusion when it returns in the initial position. Once identified the time instants gesture evolution is normalised on a 0-100 % squat cycle, so executions different speed can be compared. Note that we experienced limited cycle time duration in the gesture, so we consider an analysis based on the reference cycle suitable for our purposes. In the following results will refer to such normalised execution cycle.

3.1. Kinematics

Kinematic measurements give as output marker’s positions during the gesture. A first result is presented in Figure 2 where kinematics results depending on foot attitudes are compared. Heel and knee anterior-posterior markers positions are presented for a squat cycle. When attitude is placed on foot anterior part,
knee’s position goes in the forward direction toward foot-tip. On the contrary, when attitude is on the rear of the foot, knee remain on the back also and its position is always behind the foot-tip. This experimental evidence confirms the proper execution of the gesture as regards subject’s control of foot attitude as requested by the test protocol.

Figure 2. Heel and knee anterior-posterior positions: red front, blue middle and green rear foot attitudes.

The planar model described in 2.2 identifies articular, or relative, angles at ankle, knee and hip. Figure 3 presents an example of angular motion at the ankle for executions with and without technical shoes. Generally, graphs suggest that shoes increase the ankle range of motion, probably due to the wedge inclination under foot sole.

Figure 3. Angles at the ankle during executions with and without technical shoes.

3.2. Kinetics

Figure 4 presents a typical Ground Reaction Force (GRF) time history measured during an execution. As already mentioned, gesture dynamics is subjective and for this reason a normalisation is necessary. Nevertheless, dynamics affects the forces exchanged with the ground of course. When dealing with a rather slow execution vertical GRF can be considered constant, neglecting continuous little movements due to subject asset control. In figure 4 a rather fast execution is presented in which at about the middle of the flexion-extension cycle (50 % on the graph) there is a clear peak, about 200 N
higher than the mean. This is typical in a fast dynamic weightlift movement at maximum flexion, where we have the contribution of a fast deceleration-acceleration in the dynamics and the sudden change in muscle behaviour from extension to contraction with the contribution of muscles elasticity – *myotatic reflex*.

![Vertical Ground reaction Force](image)

**Figure 4.** Vertical GRF during a fast dynamic movement cycle

3.3. **Internal moments and foot attitude**

Internal moment at articular joints due to muscle action can be measured by inverse kinetic analysis, based on the biomechanical model. Dynamic equations define the behaviour of each model segment and starting from the distal one, the foot, where the external force is exchanged with the ground, it is possible to obtain articular moments. In figure 5 we consider two examples to compare results with and without technical shoes and with different foot attitude.

![Knee moment](image)

**Figure 5.** Example of moments at knee and ankle in different conditions: (a) - knee moment with and without technical shoes; (b) - ankle moment: rear (blue) and front (green) attitudes; knee moment rear (red) and front (black) attitudes.

4. **Conclusions**

A quantitative biomechanical analysis of squat weightlifting has been carried out to investigate the effect of foot attitude and technical shoes on weight lift kinematics and articular moments. A protocol has been developed to investigate the influence of technical shoes and foot attitude. A standard gesture cycle has been defined to compare different executions by different subjects or with different dynamics. Preliminary results quantitatively indicate that foot attitude on the front of the foot implies a higher articulation load as compared with a balanced middle sole attitude, as it was expected. Technical shoes with a low height wedge under foot sole mainly stabilise the movement and produce a slight load...
reduction on knee and ankle. Further work has to be done to analyse the overall set of data to verify results repeatability and statistical significance of the effects we have investigated. An increase in subjects’ number will give a more robust set of experimental evidences.

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