The effect of the barbell positioning on the shoulders and of the hand spacing on this barbell on the orientation of the shoulder joint reaction force in athlete performing back-squat.

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Abstract

This study has been intended to provide guidance for athlete who want to reduce their shoulder discomfort while doing back squat. Two parameters have been studied, the barbell positioning on the shoulder ΔH, varying from the upper to the lower portion of the rear deltoid and the hand spacing on the barbell ΔH_{and}, measured from the edge of the shoulder. A biomechanical static analysis has been performed and solved on MATLAB. The shoulder discomfort has been measured as being directly correlated with the orientation of the shoulder joint reaction force in the frontal and sagittal plane. Optimal values for ΔH and ΔH_{and} have thus been determined by minimizing the shoulder discomfort. Finally, the impact of morphology on these optimal positions have been studied. Overall, a small ΔH, or a high barbell positioning is preferred but individual with longer humerus or forearm would feel more comfortable with a low barbell positioning. The hand spacing ΔH_{and} must stay between 70% to 80% of the arm length, but a grip closer from the higher end may be preferred for individual with longer forearm. In any case, having hands too close from the body and a low barbell positioning must be avoid.

I. Introduction

Shoulder discomfort among athlete performing back squat is not well quantify nor understood but is still an issue that most beginners will encounter [1]. Completing a back squat with an appropriate form requires ankles mobility, knees stability, a straight back and putting its shoulders in a weak position. Indeed, to hold the barbell, shoulders must be both abducted and externally rotated, which cumulated with extended arms is the position which account for 97% of shoulders dislocation [2]. To ease the stress on the shoulders, the barbell position on the shoulders and the hand spacing on the barbell proved to be empirically effective among powerlifters [1]. However, the optimal position differs from a person to another as it looks to be a combination of morphology, and shoulders mobility. Indeed, for some people, a low barbell may help to reduce the discomfort due to the load resting on bony structure while it may induce to much strain on the shoulder for less mobile person. Being unable to account for the pain due to the loading, this study attends however, to mathematically and computationally quantify both the effect of the barbell positioning on the shoulders and of the hand spacing on this barbell on what one would call the shoulder discomfort. Joints being incredibly resistant for loading in the direction where they are backed by a bony structure, the shoulders discomfort is correlated in this study to the orientation of the shoulder joint reaction force. Therefore, an optimal position for an individual can be assessed looking at, the most favorable orientation of the shoulder reaction force by varying the two parameters selected. Finally, to quantify how versatile this optimal position may be, different morphology is tested in this study.

II. Methods

To quantify the effect of the barbell positioning on the shoulders and of the hand spacing on the orientation of the shoulder joint reaction force, a static analysis has been performed. As the problem is symmetric regarding the median sagittal plane, only the right shoulder has been arbitrarily considered. The shoulder is associated to a cube with a half edge c, and the arm is segmented into two portions, the humerus of length H_2 and combination of the forearm and the hand of length H_1, the wrist joint being neglected. The barbell is assumed to rest both on the back and in the hand, however the hand realistically having a minor role in supporting the load, reaction force due to the hand is assumed to account for ρ, a portion of the total reaction force on the back. Due to the symmetry, the weight of the barbell can be divided by two as only half of the body is studied. This half weight is called W. Regarding the barbell weight, the weight of each body's portions involved is neglected. A single muscle force F_M is assumed to model the numerous muscles surrounding the shoulder joint. This force is assumed to be in the back, as the squat position required to squeeze scapulas. To account for the variability in muscle activation induced by the hand spacing, the muscle force is assumed to be consistently parallel to the humerus in the back plane.

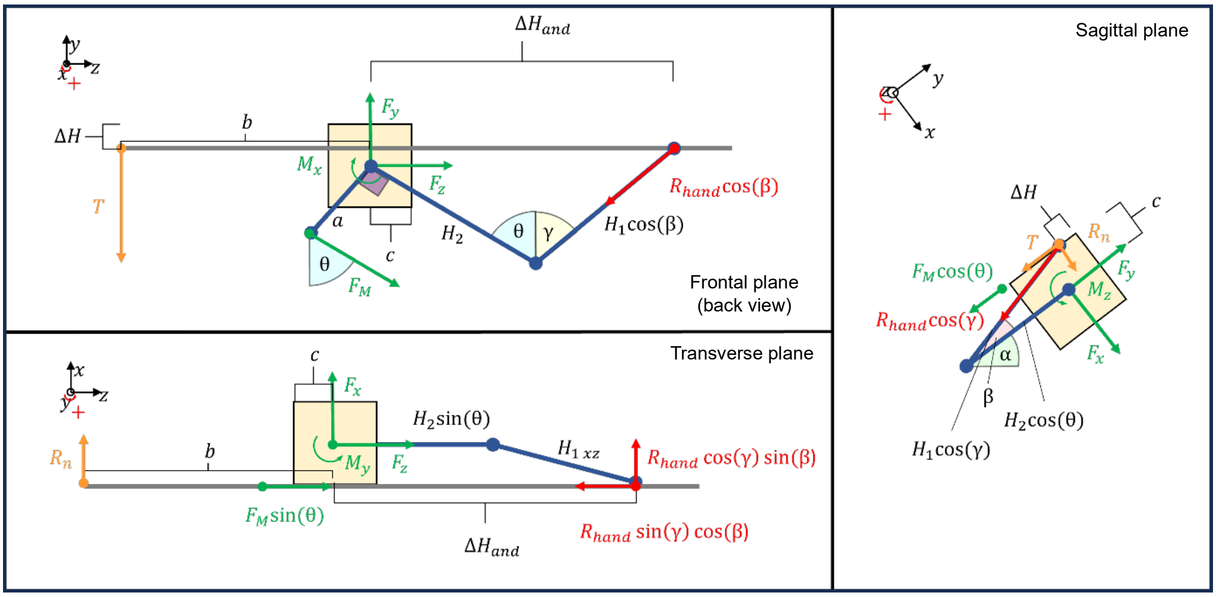

Figure II.1: Free-body diagram projected on the three plane of the problem.

On the **Figure II.1**, β is the angle made between the forearm and the humerus in the xy plane and is assumed to be fixed and account for an elbow mobility. This angle must be small as the elbow is not supposed to have any mobility in this plane as being a clinch joint. θ, γ are the angle respectively made by the humerus and the forearm with the y-axis. α is the angle made between the humerus and horizontal axis of the plane xy. The humerus is assumed to be fixed to the shoulder and its rotation make thus rotate the shoulder as a whole. α, θ, γ are directly impacted by the hand spacing ΔH_{and} and the barbell position on the shoulder $\Delta \mathrm{H}$ as follow:

$$\begin{cases} \mathrm{H_1 cos(\gamma) cos(\beta) - H_2 cos(\theta) = c - \Delta H} \\ H_1 \sin(\gamma)\cos(\beta) + H_2 \sin(\theta) = \Delta H_{and} \\ \theta, \gamma \in \left[0; \frac{\pi}{2}\right]^2 \end{cases} \qquad \begin{cases} \alpha = \tan^{-1}\left(\frac{c - \Delta H - H_1 \cos(\gamma)\cos(\beta) + H_2 cos(\theta)}{c - H_1 \cos(\gamma) \sin(\beta)}\right) \\ \alpha \in \left[0; \frac{\pi}{2}\right] \end{cases}$$

Equation II.1: Angular dependence with $\Delta \mathrm{H}$ and ΔH_{and}.

R_n, T, and R_{hand} are respectively, normal, tangential and hand reaction force exerted on the body according action reaction principle due to the loading from the weight W. Using the xy plane and assuming the weight being at the equilibrium, the following relation between these reaction force can be deduced:

$$\begin{cases} R_n = Wcos(\alpha) - R_{hand}\sin(\beta)\cos(\gamma) \\ T = Wsin(\alpha) - R_{hand}\cos(\beta)\cos(\gamma) \\ R_{hand}^2 = \rho^2(R_n^2 + T^2) \\ R_{hand} > 0 \end{cases}$$

Equation II.2: Reaction force relations.

F_{xyz}, M_{xyz} are respectively the unknown joint reaction force and moment. As the muscle force F_M is also unknown, there is a need to assume a value or a relation between variables as the forces and moment equilibrium only gives 6 equations making the system undetermined. M_y is assumed to be zero. Indeed, in this plane (top view of the shoulder), the shoulder is symmetric regarding the z axis and there is the same amount of ligament or muscle on the front and the back of the shoulders which will compensate the action of each other making M_y to be zero. This argument is not completely satisfying as it is thought that there is a predominant muscle in the back. But making M_y to be zero is a way to account for this reality. Using therefore force and torque equilibrium, the following relation can be deduced:

$$F_M = \frac{-R_{hand}\sin(\beta)\cos(\gamma)\Delta H_{and} + R_n b + R_{hand}\cos(\beta)\sin(\gamma)c}{\sin(\theta)c} \qquad F_x = -R_n - R_{hand}\sin(\beta)\cos(\gamma)$$

$$F_y = T + R_{hand}\cos(\beta)\cos(\gamma) + F_M\cos(\theta) \qquad M_x = F_M a + Tb$$

$$F_z = -F_M\sin(\theta) + R_{hand}\cos(\beta)\sin(\gamma) \qquad M_y = 0$$

$$M_z = -Tc - F_M\cos(\theta)\,c + R_n(c - \Delta H) + R_{hand}\sin(\beta)\cos(\gamma)\,(c - \Delta H) - R_{hand}\cos(\beta)\cos(\gamma)\,c$$

Equation II.3: Joint reaction force / torque and muscle force relations.

Equations II.1.2.3, have been solved on MATLAB. The parameters chosen to run the model are gathered in the **Table II.1**.

Parameters	Values	Selected from
H_1 (cm)	34 / **37** / 40	[3]
H_2 (cm)	28 / **30** / 32	[4]
c (cm)	**2,5** / 3 / 3,5	[5]
β (°)	**4** / 10 / 15	Arbitrarily selected
a (cm)	5	[4] and arbitrarily selected
b (cm)	10	[4] and arbitrarily selected

Table II.1

In **Table II.1**, the first four parameters have three different values assigned as they have been varied to see the effect of morphology on the optimal ΔH and ΔH_{and} which give the best orientation for the joint reaction force. The bold value in each list is the arbitrarily fixed value used when varying one parameter at a time. The optimal ΔH and ΔH_{and} have finally been determined studying the angle made by each component of the joint reaction force in each plane using the **Equation II.4**:

$$ang_{zy} = \tan^{-1}\left(\frac{F_y}{F_z}\right) \qquad \Delta H \in [1; 2c]cm$$

$$ang_{xy} = \tan^{-1}\left(\frac{F_y}{F_x}\right) \qquad \Delta H_{and} \in [10; 0.9*(H1+H2)]cm$$

$$ang_{zx} = \tan^{-1}\left(\frac{F_x}{F_z}\right)$$

Equation II.4: Joint reaction force angle and chosen range of variation for ΔH and ΔH_{and}.

III. Results

The result of the MATLAB simulation gives $F_y, F_M, M_x > 0$ and $F_x, F_z, M_z < 0$. $|F_M|, |F_{xyz}|, |Mxyz|$ do not vary significantly with ΔH and ΔH_{and} excepted in one point $\Delta H \approx 2c$ and $\Delta H_{and} \approx 20cm$. ang_{zx},α do not vary either and stay around $14°$ and $0°$ respectively.

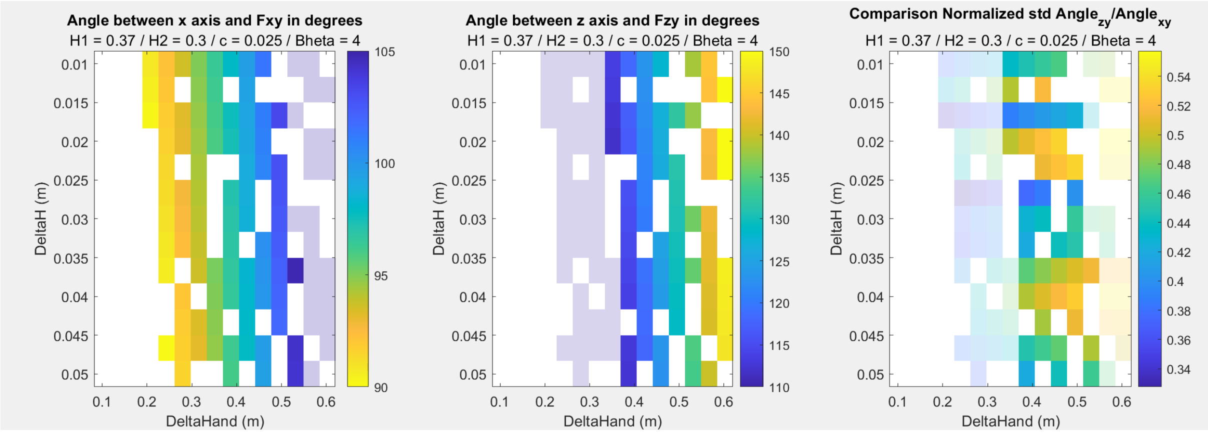

Figure III.1: Angle of the joint reaction force in the xy and zy plane with cut-off respectively above 105° and below 110°.

To better compare ang_{zy} and ang_{xy} in **Figure III.1**, the angles has been normalized by their variance calculated along the ΔH_{and} axis as there is an important variability between columns. This unable to obtain column more comparable with each other's. The set angles' cut-offs are arbitrary. Considering F_x, F_y, F_z orientation, these cut-offs have been chosen to maximize the orientation of the joint reaction force toward bony structure: In the xy plane, an angle of $90°$ is preferable compared $105°$ as the force would be in line with the humerus, and in the zy plane, an angle $150°$ is preferable compared $110°$ as it point toward the glenoid fossa composing the shoulder joint. An optimal ΔH and ΔH_{and} can therefore be evaluated looking at the maximum value of the normalized $\frac{ang_{zy}}{ang_{xy}}$, as ang_{zy} must be maximized and ang_{xy} minimized.

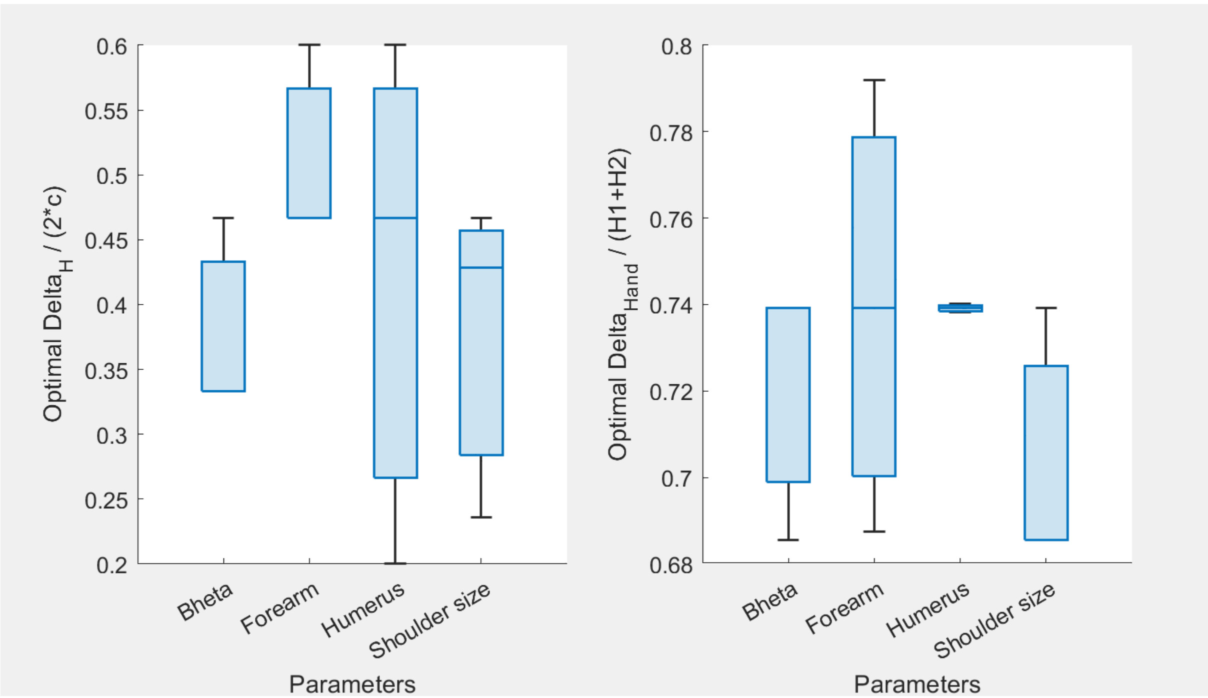

Figure III.2: Variation of the optimal ΔH and ΔH_{and} according different morphology.

IV. Discussion

The result of this simulation proves that the morphology play an important role in term of flexibility or range of motion accessible for the shoulder. Indeed, in **Figure III.1** the blank square are points where the simulation couldn't find any solution for the solving of θ,γ in **Equation II.1**. The assumption of neglecting the wrist joint can therefore be criticized as in reality, bending the wrist would be enough to reach those blank positions. But those positions would be uncomfortable anyway as is would put too much stress on the wrist joint. The α angle made between the humerus and the horizontal is probably the most concerning result of the simulation as in reality, looking at a squat from the side, one can evaluate this angle to vary between $15°$ to $50°$ during the motion. Assuming the shoulder to be a cube or the angle β to be fixed can therefore be criticized.

Despite these possible improvements, this study gives insightful guidance on the optimal barbell position on the shoulder ΔH and hand spacing ΔH_{and}. First, it well illustrates that having the hand too close from the shoulders are not a proper position to do back squat, as enlighten by the blank zone on the left side of the three plot of the **Figure III.1**. Second, the singularity observed for $|F_M|, |F_{xyz}|, |Mxyz|$ with $\Delta H \approx 2c$ and $\Delta H_{and} \approx 20cm$ where unexpectedly high value are obtained proves that having a low barbell squat with hand too close from the body is the worst position for the shoulders in term of stress. Second, varying the barbell position ΔH on the shoulder does not change that much the stress on the shoulders as shown by the small variance between the rows in the two first plot of **Figure III.1**. It therefore supports the fact that there exist both athletes using either high barbell or low barbell positioning.

However, there still exists an optimal position for both ΔH and ΔH_{and} and it may depend on the morphology as shown on the **Figure III.2**. For the first plot, a $\frac{\Delta H}{2c} > 0{,}5$ is considered to be a low barbell squat. Overall, the high barbell squat looks to be predominant to optimize the orientation of the shoulder joint reaction force and this position is also more widely used [1]. Looking at the obtained matrices to plot the **Figure III.2**, the low barbell is however a better option for people with longer humerus and longer forearm. About the hand spacing ΔH_{and}, the first observation is that the optimal ΔH_{and} is always around $70 - 80\%$, of the arm length $H_1 + H_2$. Athlete should not therefore have their hand too close from their body or their arm too extended. The main parameters making the hand spacing varying looks to be the forearm length. As it could have been expected, people with longer forearm may feel more comfortable with an increased hand spacing. However, it can be criticized that no interaction between those morphological parameters has been studied which would be more insightful and allow a better categorization of people.

Overall, despite the insight and guidance provided by this study, it still lacks supporting empirical data. Now that optimal positions can be computationally established, experimentation with a wide range of athlete with different morphology must be done to test different position and report which one looks to be the most interesting in terms of personal comfort and performance. Crossing this paper with this additional study would give final guidance for beginners trying to learn the back-squat technique.

References

[1] Avi Silverberg, PowerLiftingTechnique, Jul 28, 2023; Shoulder Pain Squatting.
[2] Rachel Abrams, StatPearls, Aug 2023; "Shoulder dislocation overview".
[3] Table 1 from Khan, Cureus. 2020 Jan; vol.12, no 1, p. e6598; doi: 10.7759/cureus.6598.
[4] Figure 2.11 from Keaveny, Tony M., Orthopaedic Biomechanics, 2006; p.50.
[5] D. M. Rispoli, B.Science, May 2009; vol.18, p.386-390, doi: 10.1016/j.jse.2008.10.012.