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# INFLUENCE OF LOWER LIMB EXTENSION EXERCISE TYPES ON MUSCLE COORDINATION: A COMPUTATIONAL STUDY

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***Abstract.*** *Lower limb exercises focused on strengthening or rehabilitation can be performed in a wide variety of equipment at gyms or training centers. They differ in the way they are built, their geometric characteristics, movable parts, movement path, subject positioning, as well as load magnitude and profile. Understanding the influence of these differences on muscle activity is important for the correct prescription of condition-specific training protocols. This work investigates the effects of different geometric parameters on muscle force profiles and coordination using a computational framework and a biomechanical model of the musculoskeletal system interacting with the equipment of three exercise types, the leg-press 45° (LP45), the horizontal leg-press (HLP) and the bar guided squat (BGS). Muscle forces were estimated along the entire range of motion for the three equipment types under different external loads using the static optimization technique. Results show that there are considerable differences in muscle coordination among the three evaluated exercise equipment types. One important observation is that the biarticular hamstrings are much more demanded in the BGS compared to the leg-press exercises.*

***Keywords:*** *Lower limb exercises, leg-press, squat, simulation, biomechanics.*

## 1. INTRODUCTION

   Lower limb exercises for different purposes, as strengthening or rehabilitation, are valuable for subjects' mobility or health. Previous authors have studied the influence of the most common exercises, as bar-squats, squat jumps, leg extension and flexion, lunge, leg-press and running on athletic performance (Jakobsen et al., 2012; Rossi et al., 2016 Padulo et al., 2017), and on shear and compressive forces at the joints (Lutz et al., 1993; Steinkamp et al., 1993; Stuart et al. 1996; Wilk et al. 1996). The main goal of most of these studies is to help prevent injuries or improve performance while prescribing the correct training program to the subject's target, since there is a large variety of equipment and exercise options that can be combined with a wide range of training protocols. However, studies investigating the influence on muscle coordination and load in terms of constructive characteristics, subject positioning and movement path are scarce in the literature.
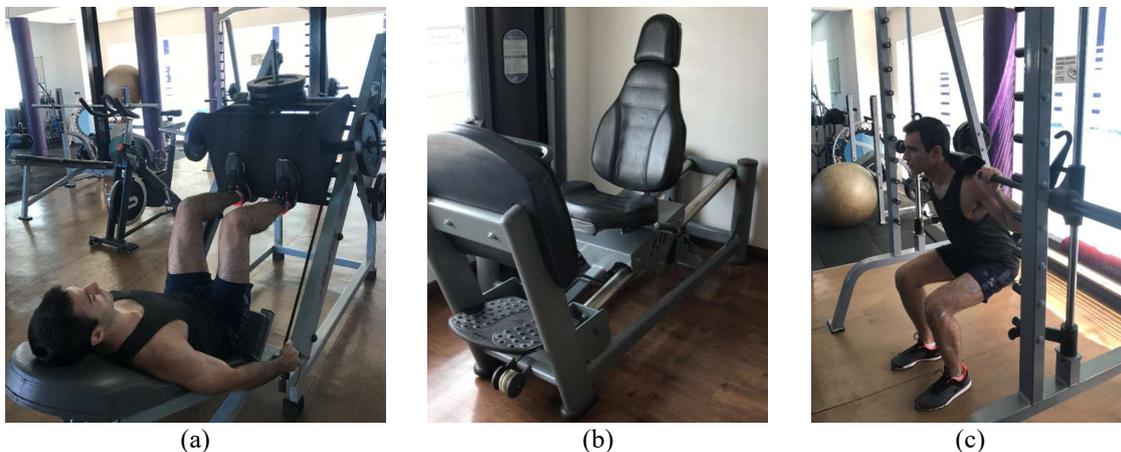


Figure 1: (a) Leg-press 45° (LP45), (b) Horizontal leg-press (HLP) and (c) Bar-guided squat (BGS).

Regarding the difficulties of current experimental studies, collecting data from a specific group of individuals is time-demanding, requires special measuring equipment and is limited in the number of parameter combinations investigated. Furthermore, to date there is no non-invasive method capable of accessing deep muscle activity *in vivo*. In this context, simulation studies in the biomechanical field arise as a feasible alternative, permitting the investigation of the influence of a plethora of different parameter and setting combinations on muscle load and coordination, replacing or preceding the costly and time-consuming experimental investigations. Bobbert (2011), for instance, investigated the effect of the force-velocity relationship in leg-press tasks using computational simulations with a model of the musculoskeletal system. In this study, only one knee extensor muscle group was considered, and the measurement of the output variables were taken at 80% of the exercise progress.

The current study investigates the influence of equipment type and parameter adjustments on muscle coordination and load profiles using a computational framework for two leg-press exercise equipment types and a bar-guided squat equipment, as shown in Fig. 1. Estimates of muscle activation and forces are obtained by means of computational simulations using the static optimization approach and a musculoskeletal model interacting with equipment models.

## 2. METHODS

The model was developed for a generic individual of 1,80 m height and 80 kg mass with anthropometric parameters estimated from Winter (2009). The subject's skeletal model is contained in the sagittal plane and composed of half of the head-trunk-arms segment (HAT), one leg, one thigh and one foot. Eight muscle groups are modeled: iliopsoas, glutei, hamstrings, rectus femoris, vasti, gastrocnemius, soleus and tibialis anterior, as shown in Fig. 2.
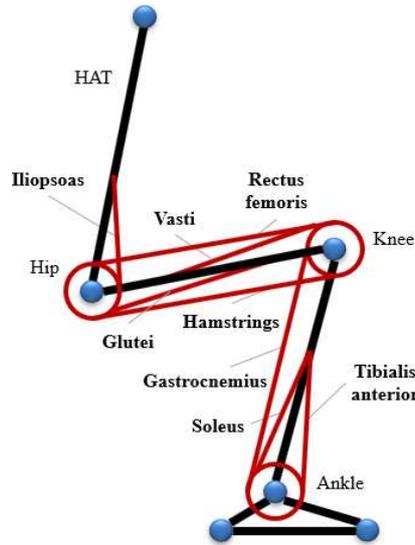


Figure 2. Musculoskeletal model.

The muscle models are Hill-type and based on a model previously described by van den Bogert et al. (2011). Since the simulations evaluate statically each position along an exercise trajectory, from the leg most flexed to the most extended position, in each exercise, only the force-length relationship is taken into account. The tendons are considered stiff and the passive joint moment profiles corresponding to the lumped effect of elastic tissue spanning the joints are adopted from Riener and Edrich (1998). Equation (1) shows the production of torque at a joint $j$,

$$\tau_j = \sum_{i=1}^{n} a_i F_{isomax,i} f_{li} d_{ij} + \tau p_j \tag{1}$$

where $a_i$ is the activation of muscle $i$, $F_{isomax,i}$ is the maximal isometric force of muscle $i$, $f_{li}$ is the force-length relationship for muscle $i$, $d_{ij}$ is the moment arm of muscle $i$ with respect to joint $j$, and $\tau p_j$ is the passive joint moment at joint $j$.

The three exercise types are modeled by means of planar multibody systems, Fig. 3. Both leg-press exercises are modeled with two rigid bodies, the thigh and the leg connected by ideal hinge joints. In the LP45, Fig. 1 (a) and Fig. 3 (left), the hip is considered fixed to the equipment and the ankle joint slides along a straight path. In the HLP, Fig. 1 (b) and Fig. 3 (center), the ankle joint is fixed to the equipment and the hip slides along a straight path. The BGS, Fig. 1 (c) and Fig. 3 (right), is modeled with three rigid bodies connected by hinge joints, with the ankle connected to the ground and the shoulder (red in Fig. 3) sliding along a straight vertical path. In all the exercises, the variable $D$ is adopted to represent the exercise progress and corresponds to the ratio between the hip-ankle distance and the total leg length. It

assumes 0 when the ankle is on the hip, and 100% when the legs are fully extended. The movement is analyzed in intervals of 2%.

In both leg-press exercise types, the models have a single degree of freedom (DoF), and so, $D$ is the only variable necessary to represent the system configuration. In the BGS, an additional DoF arises and the model has 2 DoFs. In this exercise type, the leg angle relative to the horizontal is also used together with D to describe the system configuration. This variable was considered as an optimization variable along with the muscle activations and reaction forces in the translational joints. Also, in order to avoid positions favorable to knee injuries, this angle was limited such as the horizontal knee position does not surpass the toe, as described by Fry et al. (2003).
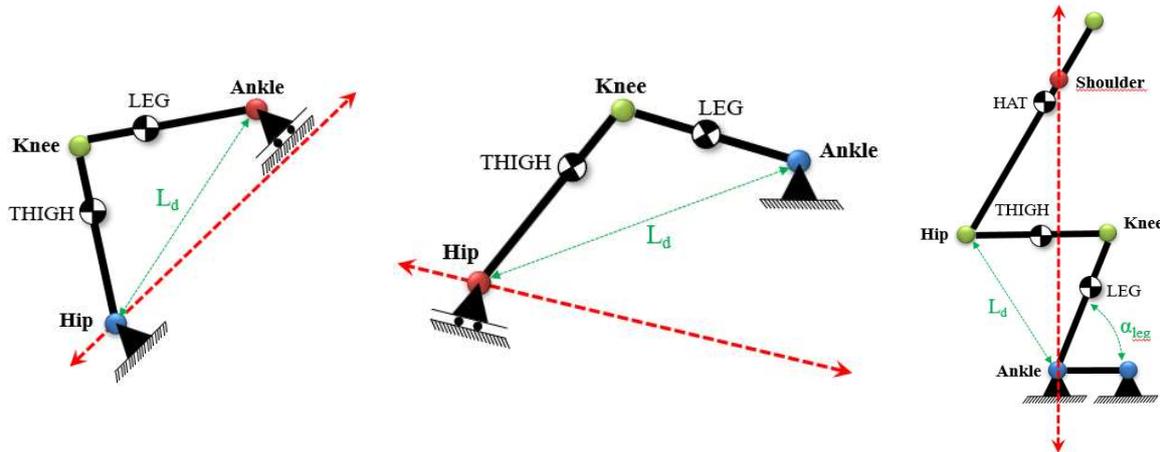


Figure 3. Kinematic model of the LP45 (left), HLP (center) and BGS (right) exercises. $L_d$ is the distance between hip and ankle. $\alpha_{leg}$ is the angle between leg and the horizontal reference line.

At every step, static equilibrium is computed and muscle forces and activations are estimated by solving a static optimization problem. The adopted objective function for the static optimization was the sum of the cubed muscle activations as a proper cost function for lower limb activities, preventing muscle co-contraction and fatigue (Erdemir et al., 2007). Additional constraints were added to the BGS exercise to guarantee that the shoulder was always moving upwards and to avoid overlapping of lower limb segments. Physiological limits are imposed according to reference values reported in van den Bogert et al. (2011).

To investigate the influence of the geometric characteristics of the equipment, 3 different scenarios were analyzed, considering variations in the HAT angle in the leg-press exercise types, and foot positioning in the BGS, as shown in Tab. 1. The HAT angle describes the trunk angle with respect to the horizontal (anti-clockwise) and can frequently be adjusted in the leg-press exercise equipment. This angle affects muscle lengths and force capacity through the force-length relationship of the muscles attached to the hip. It also affects the passive joint moments. In the BGS, the foot positioning can be adjusted by placement of the foot on the ground with respect to the vertical, guided trajectory of the shoulder joint, represented by the dashed red line in Fig. 3. Positive values correspond to foot placement in front of the vertical trajectory.

Table 1. Characteristics of the exercises evaluated in three different scenarios.

| SCENARIO | HAT angle [°] | | | Foot plate angle [°] | | | Foot positioning [m] | | |
|:---:|:---:|:---:|:---:|:---:|:---:|:---:|:---:|:---:|:---:|
| | LP45 | HLP | BGS | LP45 | HLP | BGS | LP45 | HLP | BGS |
| 1 | 140 | 100 | - | 70 | 80 | - | 0 | 0,175 | 0 |
| 2 | 150 | 115 | - | 70 | 80 | - | - | - | 0,11 |
| 3 | 160 | 130 | - | 70 | 80 | - | - | - | 0,22 |

In the first part of this work, the investigated exercise configurations were matched to the ones measured in real equipment available in two gyms. For each exercise equipment, external resistive loads of 0 to 200 kg in 10 kg steps were simulated and the maximum load was taken when the total movement amplitude started to decrease, which indicated muscle saturation. The maximum mass before infeasibility is observed in certain system configurations was 170 kg for the LP45, 140 kg for HLP and 110 kg for the BGS. Then, light (without external load), medium (median) and heavy loads (respective maximum mass) simulations were registered.

## 3. RESULTS AND DISCUSSION

The activation profiles along the movement of the most important lower limb muscle groups are shown in Fig. 4 and differ substantially among the exercise types. As the resistive load increases, muscle activations increase and even achieve maximal activation value, corresponding to 1, for the heavy load in certain movement ranges. As loads increase, the tendency is that the range of motion decreases as a result of infeasibility due to muscle force saturation, observed in the beginning of the movement range where joints are most flexed. As movement proceeds and joints are extended, muscle activation decreases to nearly zero as leg extends fully. In general, the BGS elicits the larger activation magnitudes, particularly in movement mid-range.

As expected, the large monoarticular lower limb joint extensors of hip (glutei), knee (vasti) and ankle (soleus) are consistently activated in all investigated exercises. The vasti group showed to be the most activated during the entire amplitude of all the exercises. With light loads, BGS is the only exercise that activates the muscles significantly because of the load due to the individual's own body weight, especially of the HAT segment.

The LP45 exercise is the one with the lowest activation magnitude compared with the others in all loads used, with exception for the soleus group, in which all the exercises tend to require it similarly. Also, the LP45 is the exercise with the lowest amplitude of movement. In the most flexed position, the muscle groups are not fully activated, but the physiological limitations of the joint angles make further flexion impossible.

Glutei and hamstrings groups tend to be more activated in the most flexed positions of the leg-press exercises decreasing rapidly in the mid-range. A special attention is given to the hamstring group. Even though it is a knee flexor, its activation is also present, mainly in the BGS exercise. This observation indicates the BGS could be a more appropriate exercise for the training and rehabilitation of the hamstrings than the LP45 and the HLP, which agrees with observations by Wilk el al. (1996), who found larger hamstrings activation during the power squat exercise in anterior-cruciate ligament rehabilitation exercises.
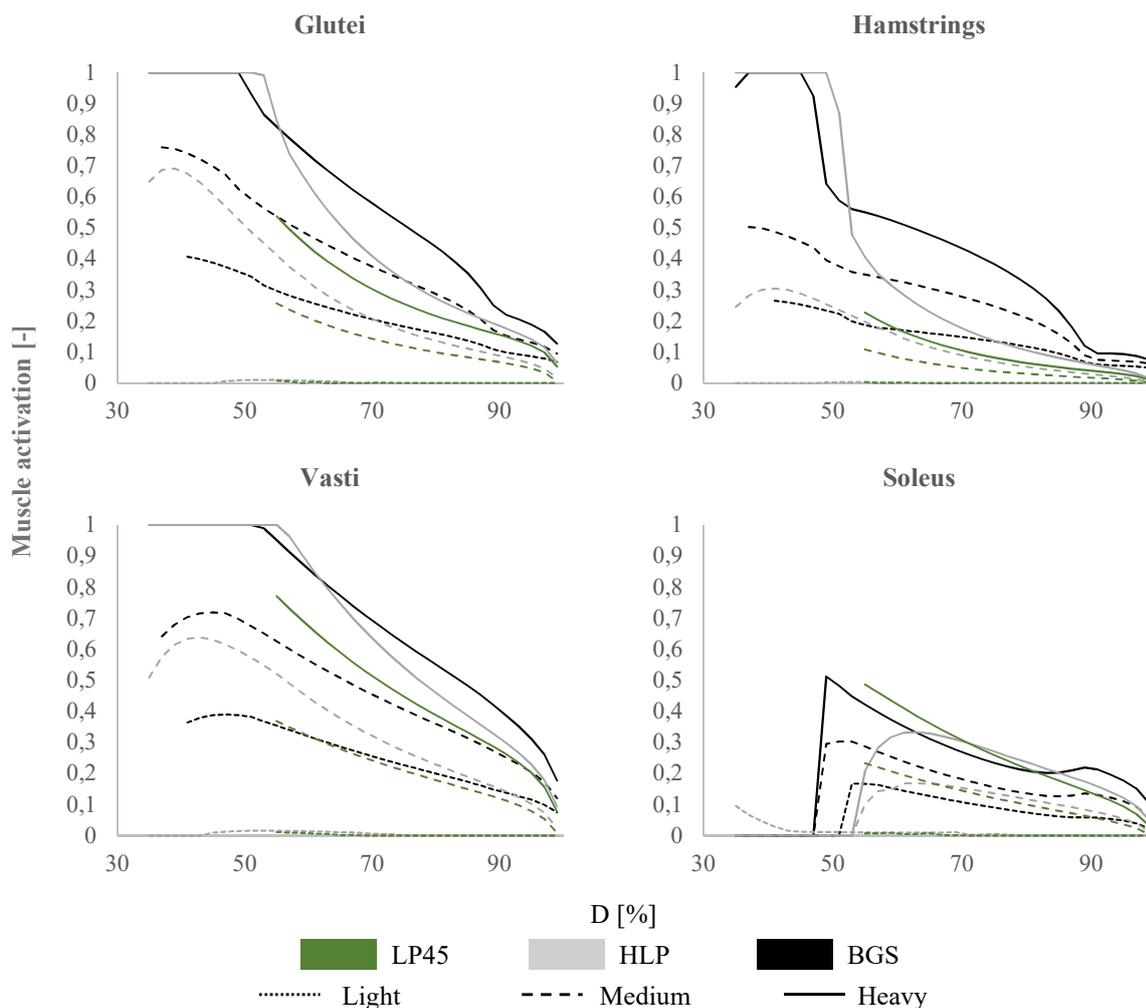


Figure 4. Activation profile for the best match configuration with real equipment.

In the second part of the investigation, the variations of the exercises were simulated. Figure 5 shows the total work done by each muscle along the entire extension motion. The vasti group, a monoarticular knee extensor, tends to be less sensitive to the different scenarios of the exercises, as expected, but notably, is far more demanded than the other groups in both leg-press exercises and BGS. The glutei group showed a high sensitivity to different HAT angles in leg-press exercises, showing a 239% increase in the muscle work in the HLP. It can also be noticed that the work of glutei is much higher in BGS exercise in comparison to the leg-press exercise. The hamstrings group showed a high sensitivity to HAT angle variation in leg-press exercises and in the BGS its work slightly decreases as the foot position increases. The higher levels of work in the hamstrings group, a bi-articular muscle spanning hip (extensor) and knee (flexor), in the BGS exercise caused a co-contraction of knee extensor and flexor muscles. In general, the soleus group showed to be the less demanded in all exercises.
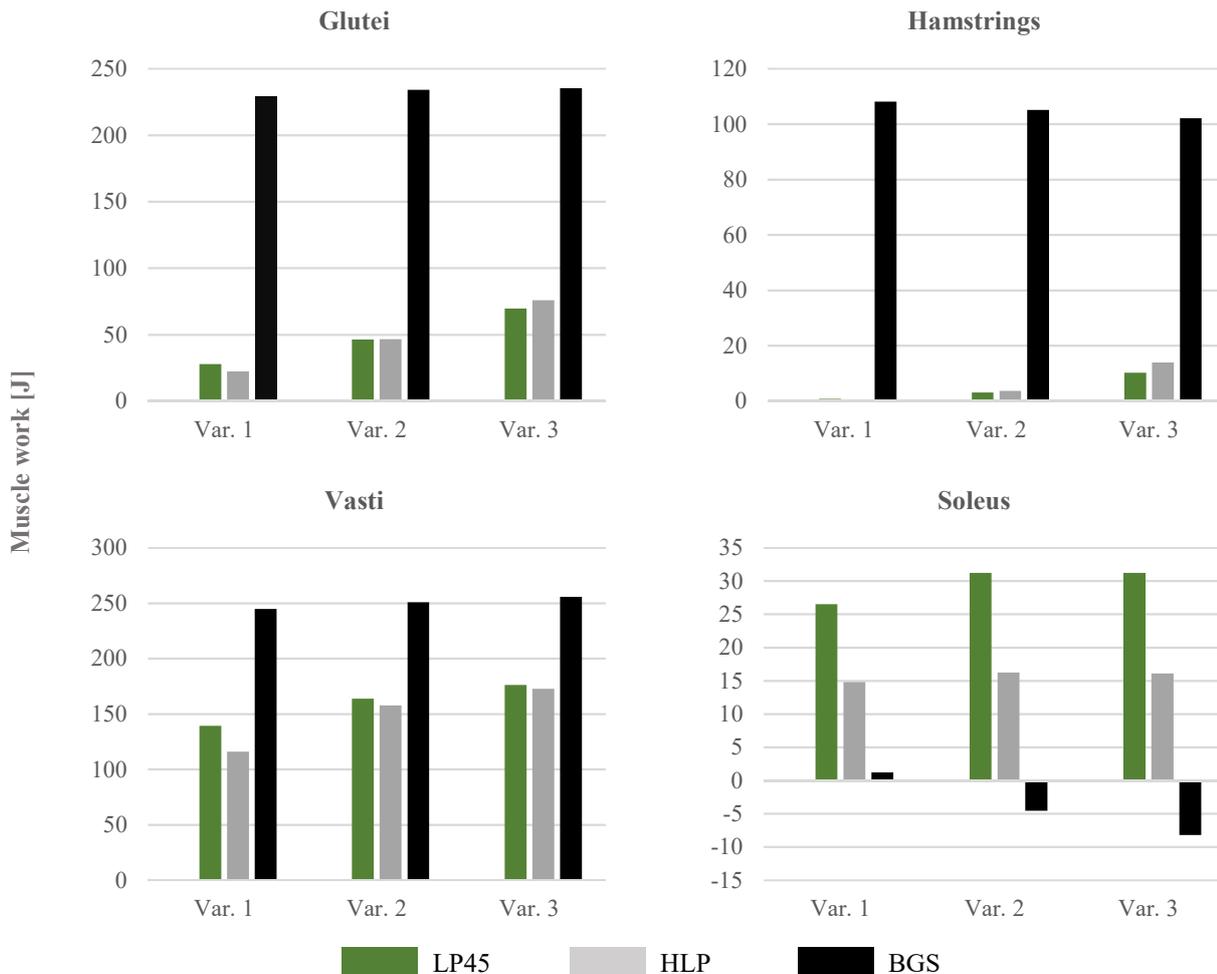


Figure 5. Total muscle work in each exercise variation.

## 4. CONCLUSION

The simulations confirmed the existence of differences among the investigated exercises with respect to muscle coordination and force magnitudes along the range of motion. The hamstrings, for instance, are consistently more activated in the BGS compared to LP45 and HLP, which indicates that this exercise is a better option if the strengthening of this muscle group is desired. Also, the activation level of the LP45 is the smallest of all the exercises evaluated and also corresponds to the exercise with the shortest excursion within physiological limits. For the heavy loads, BGS and HLP elicit full activation of glutei, vasti and hamstrings when the joints are most flexed, what limits the movement amplitude and determines the maximum external weight supported of 110 and 140 kg, respectively.

The study also showed the importance of equipment adjustments and constructive characteristics, which were shown to affect muscle loading. Muscle activation in leg-press exercises is sensitive to HAT angle adjustments. In the case of BGS, the results show that foot positioning do not affect muscle activation profiles substantially.

In conclusion, this study shows the important differences between different leg extension exercises in terms of muscle activation level and coordination. This evidences the need for careful exercise equipment selection and adjustment to guarantee correct prescription of training programs according to subject-specific goals.

## 5. ACKNOWLEDGEMENTS

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