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ORIGINAL ARTICLE

Improving the design of squat machine using motion capture and virtual prototyping

Lorenzo Mariti · Pier Paolo Valentini

Abstract Dynamic squat is one of the most executed fitness exercise. Its use is widespread both for rehabilitation and training purposes. Several typologies of the squat exercise can be performed. The most important are the front squat and the back squat. In the front squat the barbell is held in front of the body across the clavicles and deltoids, while in the back squat exercise the bar is held on the back of the body at the base of the neck. In this paper we will refer to dynamic back squat. The squat exercise can be performed with or without the help of a machine that has the scope of guiding the person during the movement and ensuring his stability and safety. The use of this type of machine is often necessary when the workout is heavy and the risk of incorrect exercise and injuries is high. On the other hand, the rigid structure of this device often overconstrains the lifting movement. From all these observations, the purpose of the paper is to discuss an alternative design of a mechanism able to maintain the advantage to allow a free-body execution and to preserve the safety of the athletes as well. The proposed mechanism has been designed starting from an anthropometric study on the squat movement. This has been performed by using a motion capture system and applying computer-aided engineering techniques. The design activity started from the experimental investigation of the trajectory of the barbell during the natural execution of the unrestricted back squat exercise. The tests have been performed on several subjects with different mass, anthropometry and gender. In a second phase, the data have been processed and analyzed and a specific mechanism, able to reproduce the natural trajectories, has been synthetized. Finally, the design and optimization of the entire structure has been performed through the use of virtual prototyping techniques.

Keywords Squat · Motion capture · Virtual prototyping · Design optimization

1 Introduction

According to several physiologists [1–3], the squat is one of the best fitness exercise for toning up quadriceps, hamstrings and gluteus maximus muscles, among the others. In addition to muscle strength, it improves balance and intermuscular coordination.

It is commonly believed among athletes and coaches that the squat enhances athletic performance and minimizes injury risk [4–6]). For these reasons, its use has been recently extended for prevention of osteoporosis, fractures and back pain [7]. Moreover, it helps the increase of bone density and thickness of ligaments, promoting tendon elasticity as well [8].

In the last few years all these positive aspects, together with the fact that dynamic squat is classified as closed kinetic chain exercise, have led doctors and therapists to use it also for rehabilitation purposes.

In order to focus on different aspects of squat exercise, it is important to distinguish among different squat typologies.

The main difference is between back and front squat. They are both multi-joint exercises used primarily to develop and strengthen the muscles of the lower body

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(quadriceps, gluteus, and hamstrings). In the front squat exercise the barbell is held in front of the body across the clavicles and deltoids as shown in Fig. 1, while in the back squat exercise the bar is held on the back of the body at the base of the neck or lower across the upper back as shown in Fig. 2. A lot of studies have been carried out on the biomechanics of the back and front squat exercises ([9, 10], for example). For the purposes of this investigation, we want to focus only on the back squat. Since it can be performed as a dynamic or isometric exercise, in the following we will refer to the dynamic back squat (the one depicted in Fig. 2).

According to [11], the correct execution of the dynamic back squat requires that the subject has to first place his feet flat on the floor. Then he has to locate the barbell over the trapezius muscle paying attention to avoid the placement over his neck. The barbell must be placed as far back as possible, in order to properly distribute the weight and ensure a safe execution of the exercise. The hands have to be placed around the barbell so as to ensure a safe and comfortable grip. The hips must be pushed forward and the abdominals pulled in. The lower back should be kept slightly arched. During the whole execution the knees should stay aligned with the toes without advancing beyond them and the heels should remain directly under the barbell. The movement can be divided into two phases: the down-squat phase and the up-squat phase. In the first phase the subject, in a controlled manner, must lower slowly until knees and hips form an angle of about 90° and the thighs are parallel to the floor. During the down phase it is important to keep the back slightly arched. In the second phase more power is generated because the legs are pushing to overcome the resistance of the gravity force. In this phase, the subject must push on his heels to return to the starting position.

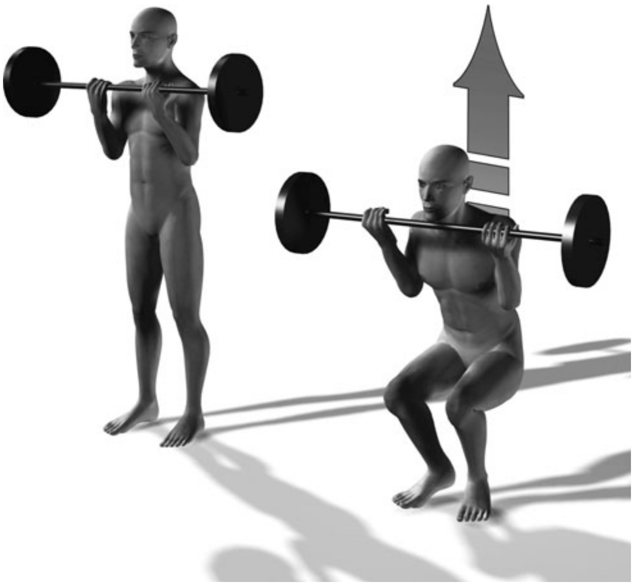

Fig. 1 Pictorial description of the front squat movement

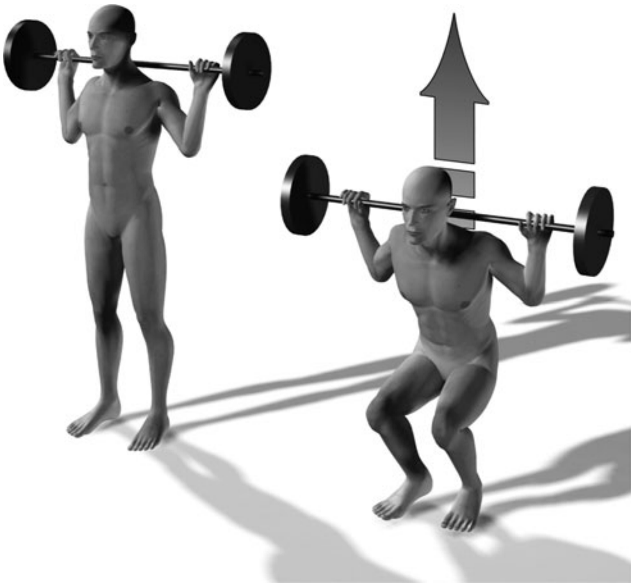

Fig. 2 Pictorial description of the back squat movement

The most common methods for executing dynamic back squat exercise are unconstrained barbell squat and machine-driven squat.

The main difference between the two methods is that with a machine, the individual is forced to drive the barbell along a given trajectory (the one set on the machine by the designer). By doing the exercise with the free barbell, one has the possibility to adapt the movement to his own biomechanics. In fact the natural movement is in general different from one person to another and the unrestricted movement highlights the differences in performance among the subjects.

The back squat machine promotes safe lifting in terms of potential dropped barbell and lifts to failure point. However, the alignment of the lift adopted when using the squat machine can still expose the lifter to injury.

Although it seems to be a simple exercise, one of the main problems associated with the squat is the difficulty in executing it correctly. The athlete or the person who is performing the squat, must pay attention to the safety of the exercise and to the risk of injuries.

The *American College of Sports Medicine* (ACSM) in a report on the safety of the squat exercise stated that, if it is not well executed, this exercise can cause damage to the knee joint and the associated ligaments. Performing squat while overly fatigued may place the athlete at risk of losing control of the squat movement, allowing a twisting motion at the knee and increasing the potential for meniscal injuries. Time for adequate recovery should be allowed (both within the exercise session and from one exercise session to the next), and the resistance and repetitions should be adjusted appropriately.

Another area of concern for safety in the squat exercise is the low back. If the lift is not properly performed, the forces at the low back may be intense enough to cause injury. The most common errors that may lead to back problems include lifting excessive weight and leaning over too far so the weight is lifted by the back and not the legs and hips. Squatting with resistance placed on the upper back across the shoulders does increase the compressive forces on the spine. Maintaining an erect posture helps to evenly distribute the forces on the spine, and to decrease the chance of injury. Forces at the lumbar spine on half-squats with a loaded barbell were determined to be 6–10 times the body weight. To reduce both spinal compressive forces and shear forces, the athlete should have the necessary flexibility of the knee, hip and spine to maintain an upright posture during the squat.

A lot of debates and studies have been made about the dangers associated with the squat exercise. These studies can be helpful not only for the comprehension of the fitness exercise, but also for the aspects related to the ergonomics of any lifting act.

Chandler and Stone [12] proposed a detailed review of the literature on the squat exercise in athletic conditioning.

Escamilla [13] proposed a review of the works about the biomechanics of the dynamic squat exercise. He mainly focused on the contributions on the knee biomechanics, paying attention to the forces acting on it. In fact one of the major concerns of physiologists is about the high loads acting on this joint.

Lutz et al. [14] compared the tibiofemoral joint forces during open and closed kinetic-chain exercise, in order to demonstrate the advantages of a closed-kinetic-chain.

In order to give an experimental measure of these forces, Bosco et al. [15] proposed a validation of a new dynamometer for the evaluation of dynamic muscle work.

An analysis of the dangers associated with low back pain (LBP) has been presented by van Dieën et al. [16]. They compared two different lifting techniques: stoop and squat. In fact, lifting is the best documented risk factor for this disorder.

Considering this background, the idea behind this work is to merge the advantages of unrestricted and constrained movements. The objective is therefore to study the movement associated with the barbell squat (i.e., the exercise performed without guide or constraint) in order to design a mechanism able to reproduce the right movement for each person. A requirement of the mechanism is the capability to be suitable for supporting athletes with different anthropometric features.

The presented investigation starts from the motion analysis of the unrestricted execution of dynamic back squat exercise. This analysis is performed with the use of a non-invasive system in order to allow the athlete to move correctly and ensure the tests' repeatability.

Previous studies on similar topic [17–19] make use of an optical motion capture system, that has the capability to acquire quantitative information about the mechanics of the muscular–skeletal system during the motion of bone or body segments.

A first-level simplified analysis can be performed on the basis of simple television coverage. However, for a specific and detailed analysis, high-frequency systems and infrared sensors are required to track the trajectory of some marked points.

Typically, an opto-electronic computer combination based on closed-circuit television images, with or without video-tape storage, is used to track the motion of small reflective markers attached to the body.

Although the motion capture system has already been used several times in the industry of gaming and entertainment, it is not the first time that it is used for the analysis of sports movements. For example, Kenny et al. [20] used motion capture system for the developing a musculoskeletal computer model for the energy analysis of golf swing movement. Delay et al. [21] performed an analysis of the golf putting movement through the use of a SELSPOT system.

The contents of the paper are organized as follows. In a first section the details of the experimental setup and methodologies are presented. Then the analysis of the barbell trajectories together with their variability inter- and intra-subject, are reported and discussed. In the last section, the outline for the design of a specific mechanism is described starting from the correlation between barbell trajectories and human characteristics.

2 Experimental analysis

The experimental investigation aimed to observe the unrestricted squat movement executed by several people in order to record and analyze the trajectories of the longitudinal barbell and the body posture. All the experiments have been conducted using an infrared motion capture system. In order to perform a statistical data treatment and comparison, a specific test protocol has been defined.

The main idea is to analyze the curve of the barbel with *zero load*. Within these conditions, it is assumed that the human body will follow the more natural path. Therefore, we decided to perform a squat test with a light wooden barbell. In this way the individual can execute the movement in a comfortable way setting a trajectory not affected by high muscular effort.

2.1 Experimental setup

In this section the description of the experimental setup is presented. In particular, we want to pay attention to the capture volume, the placement of the cameras, and the hardware devices used.

The implemented system is particularly apt for the capture volume and the speed of execution of the exercise.

All the experimental tests are performed using the Optitrack Flex V100R2 hardware and the Arena Motion Capture Software (http://www.naturalpoint.com/optitrack). The implemented acquisition system is composed of five infrared synchronized cameras that have been mounted around the capture volume (see Fig. 3). The acquisition frequency of 100Hz seems adequate for the type and speed of movement to analyze.

The capture volume is half a cylinder of 1 m of radius. In order to follow and acquire the entire movement of the subjects, each camera has been placed at a different height from the floor.

The performances of a motion capture system depend mainly on the accuracy with which the system is calibrated. Once the capture volume has been defined, the dynamic and static calibration have been executed. Through the *dynamic calibration* procedure, the optical distortion due to the cameras lenses, and any other nonlinearity in the system, is measured by moving a *wand* with a reflective marker at its tip through the whole capture volume. After the calibration we measured a residual value for the cameras of 1.3 mm. A correction factor is than calculated and applied to each frames. In the *static calibration* an *L-shaped* object equipped with three reflective markers is placed in the capture volume for fixing the origin and direction of the axis of the ground reference frame.

Fig. 3 Capture volume and cameras disposition

2.2 Experimental protocol

Once the capture volume has been defined by the position of the cameras, and static and dynamic calibrations of the motion capture system have been completed, we started to define a standard procedure for the execution of the test. Each test, requires the athlete to execute the barbel squat movement as described in Fig. 2. During the *down-squatting phase*, he may lift the heels off the ground and must lead the knees vertically aligned with the feet.

In order to develop and refine a body control mechanism, required for proper execution of the exercise, each squat execution has ben repeated 10 times (5 executions have been used for warming up and 5 executions have been acquired an processed).

Data were collected for 60 people, 30 men and 30 women. None of the tested subjects is a professional athlete or practices sport in intensive way. Details on the age, mass, height and sport background are reported in the tables of the Appendix 1.

The subject executes the test within the capture volume that has been previously set. A rectangle on the floor (see Fig. 4) indicates the location of the feet for the exercise. Three spherical reflective markers have been attached to the barbell in order to acquire its position and attitude. Two markers have been attached to the two edges, one in the mid-point. Anatomical landmarks of the body (knee, ankle) have also been monitored. Although they are not meaningful for the present study, they can be useful for a thorough biomechanic investigation of the human body. The objective of this research is not to study the biomechanics and kinesiology of the lift act, but only the trajectory of the barbell. The kinesiology of the movement will be analyzed in depth and published later in another context.

Three snapshots of the unrestricted squat during a test are shown in Fig. 4.

As we said, the main goal is to see how the human body behaves without any limitation. For this reason we chose to focus on the unrestricted movement. Since we monitored only the trajectory of the barbell, the acquisition of the restricted movement would not offer significant results.

3 Data analysis

The output data of the experimental phase contain information about $X-Y-Z$ coordinates of the markers placed on the moving bodies. Since our interest is focused only on the trajectory of the barbell, we reduced the amount of data going to perform only a planar analysis on the $X-Z$ plane.

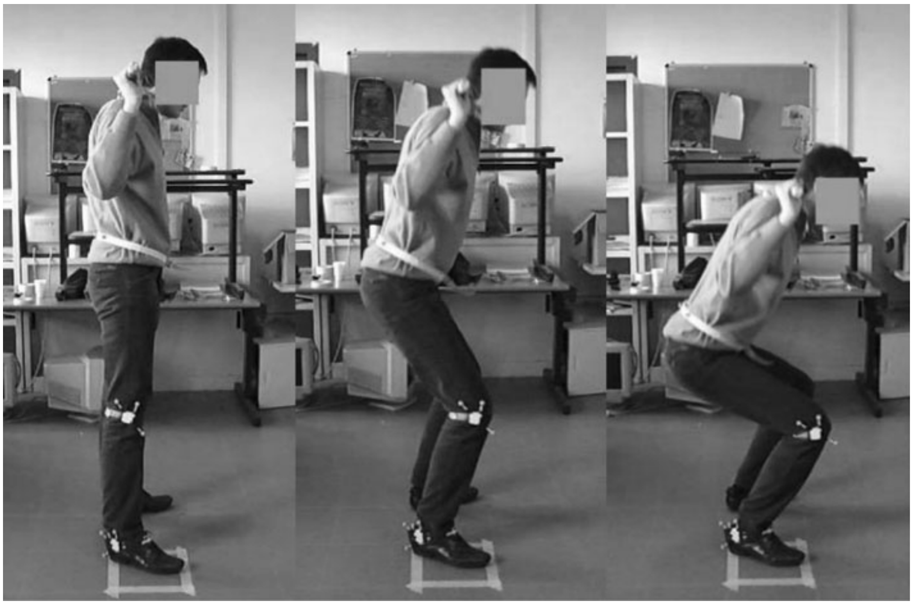

Fig. 4 Unrestricted squat experimental execution

In the chosen reference frame, this plane represents the average sagittal plane of the human body (see Fig. 5).

Therefore, we have considered the barbell midpoint trajectory projected on the $X-Z$ plane.

The origin of the ground reference frame is placed on the floor. It is 50 cm posterior to the distal end of the first metatarsal, as described in Fig. 5.

Fig. 5 Unrestricted squat phase and trajectory to be recorded

The squat movement can be represented as an open kinematic chain linkage with different degrees of freedom (DOF). This means that in order to execute the exercise, the body has to carry out a control mechanism. This mechanism depends not only of the subjects' aptitude and perceptive skills, but also on training. In the executed tests we tried to give to the subjects the possibility to acquire familiarity with the movement, by executing five attempts. We found that as the number of attempts increases, the stability of movement improves and the trajectories are more regular.

Figure 6 shows an example of the curve of the fifth attempt, projected on the sagittal plane.

Observing Fig. 6, one can note that the barbell midpoint trajectories for the up and down phases of the unrestricted movement are very close and that the up-squat phase can be approximated by an inclined straight line.

The first point that we want to focus on, is the trend of the curves with respect to the longitudinal human body axis. Fig. 7 shows that, with respect to the vertical line passing through the shoulders and feet, there is an average deviation of some centimeters. This deviation is function of the height of the person executing the test and it is very slightly affected by the gender of the subject.

Through this observation is clear that the barbell do not follow a straight trajectory. This is in contrast to many gym machines in which the barbell is constrained to vertical straight rails.

Another evidence in Fig. 7 is that, as the height of the individual decrease (starting position of the barbell), the horizontal displacement increases. Fig. 8 shows this trend for different height percentiles.

The next step in the data analysis has been the interpolation of the experimental curves. The scope is to obtain an

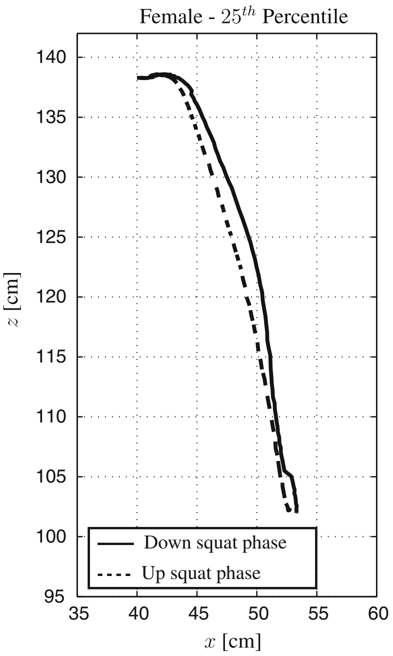

Fig. 6 An example of the acquired trajectory of the barbell mid-point projected on the sagittal plane: unrestricted motion

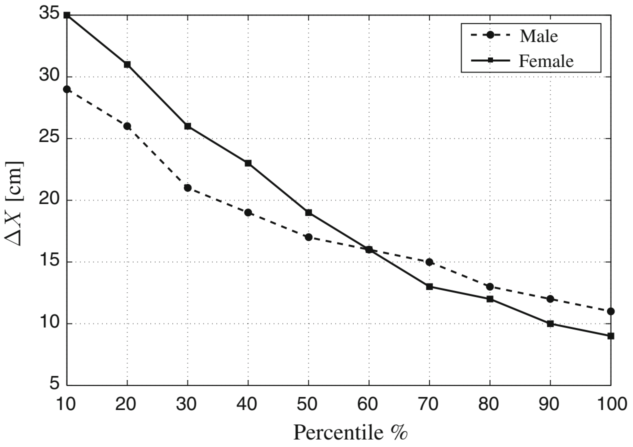

Fig. 8 Maximum horizontal displacement of the barbel during the whole unrestricted squat exercise for different height percentile

analytical expression for each curve, in order to perform an anthropometric analysis based on the results shown in Fig. 8 and to design a mechanism able to trace those patterns.

We mainly focused on the up-squat phase, which is the most important part of the exercise because the muscular effort is greater. Such approximation has more validity if one considers that the the two phases tend to overlap when the individual executes several attempts.

For this scope, a regression of the experimental data has been performed. The simplicity of the curves, suggests adopting a second degree polynomial approximation. The analysis shows a good confidence with the experimental data as it is possible to see in Fig. 9 for a generic test.

The extrapolated results of the interpolations are reported in Table 1 for men and Table 2 for women.

In Fig. 10, the polynomial expressions of the curves describing the unrestricted up-squat phase are plotted for both men and women.

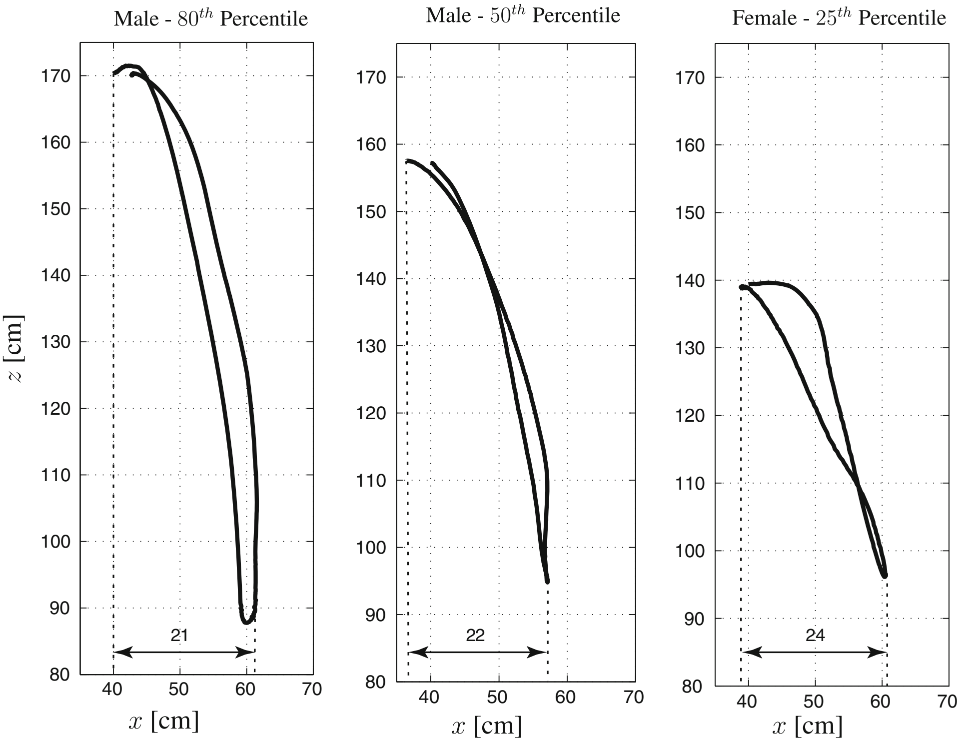

Fig. 7 Horizontal displacement observed during the exercise for three different individuals: unrestricted motion

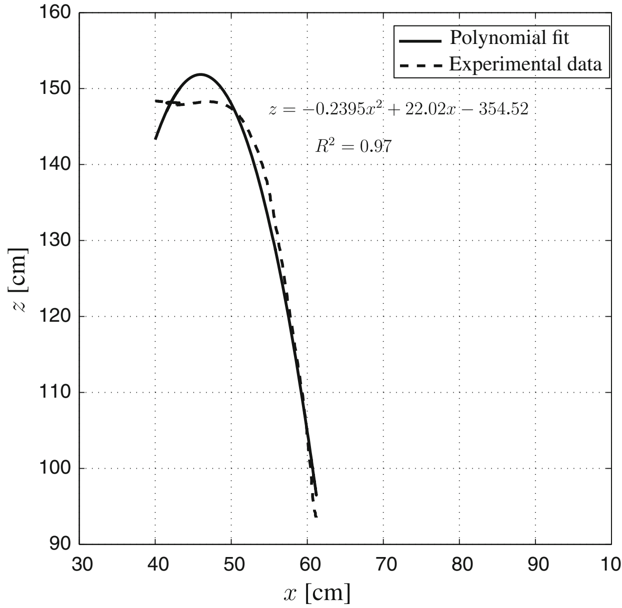

Fig. 9 An example of data fitting for a male 46th height percentile subject: unrestricted up-squat phase

Table 1 Quadratic polynomial coefficients function of men's height percentile

Percentile	Men: coefficients (average values)		
	a	b	c
10th	−0.7501 ± 0.005	61.49 ± 0.2	−1138 ± 5
20th	−0.4857 ± 0.006	36.91 ± 0.3	−565 ± 5
30th	−0.7150 ± 0.004	60.06 ± 0.2	−1116 ± 6
40th	−0.7980 ± 0.003	67.11 ± 0.4	−1259 ± 5
50th	−0.3937 ± 0.007	34.50 ± 0.1	−594 ± 4
60th	−0.2633 ± 0.007	23.48 ± 0.2	−363 ± 5
70th	−0.2279 ± 0.006	19.20 ± 0.2	−240 ± 4
80th	−0.2009 ± 0.005	17.01 ± 0.3	−193 ± 5
90th	−0.3499 ± 0.005	31.48 ± 0.2	−530 ± 5
100th	−0.2211 ± 0.004	19.23 ± 0.4	−236 ± 6

Observing the patterns of the various curves, one can note that the inclination of the rectilinear portion at the beginning of the up-squat phase, is similar among the different subjects. It means that with a translation along the X-axis, one curve can be superimposed onto another with reasonable accuracy.

These results are the starting point for the following mechanism design phase. In particular, we want to find a law that relates the horizontal displacement of the curves to the value of the height percentile. It is possible to find this law by measuring the displacement δs along the X-axis from one curve to another, in the rectilinear portion in which the inclination is similar.

Table 2 Quadratic polynomial coefficients function of women's height percentile

Percentile	Female: coefficients (average values)		
	a	b	c
10th	−1.1667 ± 0.002	98.01 ± 0.1	−1923 ± 2
20th	−0.6364 ± 0.003	54.09 ± 0.1	−1012 ± 2
30th	−0.6480 ± 0.001	55.29 ± 0.2	−1041 ± 3
40th	−0.3499 ± 0.003	29.42 ± 0.3	−477 ± 2
50th	−0.2523 ± 0.002	20.95 ± 0.1	−293 ± 1
60th	−0.3182 ± 0.002	26.73 ± 0.1	−415 ± 4
70th	−0.2917 ± 0.003	24.50 ± 0.1	−363 ± 4
80th	−0.2916 ± 0.001	24.48 ± 0.2	−361 ± 1
90th	−0.2692 ± 0.002	22.08 ± 0.1	−299 ± 2
100th	−0.2501 ± 0.002	21.05 ± 0.1	−283 ± 2

Figure 11 shows the δs pattern for different height percentile values. All the values are normalized to the 100th percentile. This means that, in order to overlap the curves, every person with a value of the height percentile less than 100th, has to execute the exercise in a forwarded horizontal δs position.

Starting from this consideration, it is possible to design a mechanism that has to be able to reproduce a single trajectory. The athlete will adjust his horizontal position (along axis X) at the beginning of the exercise in order to ensure that the mechanism will guide the barbell along the correct part of the path.

4 Mechanism design

Considering the results shown in Tables 1 and 2, the second degree approximated curves have small curvatures. It means that they are close to be rectilinear. This evidence leads to choose a mechanism to guide the barbell among those generating straight line trajectories. With a small modification of the dimensions, it is possible to obtain a low curvature trajectory very close to those computed in the previous section.

Scientific literature and industrial applications report a lot of possible straight-line generator mechanisms [22, 23].

The one that we chose for our scope is the Scott-Russell mechanism depicted in Fig. 12. This choice is mainly due to the simplicity of this mechanism. It is composed of a crank, a rod and a slider. If the relationships among the dimensions indicated in figure are respected, the tip point P of the crank will describe a straight line trajectory.

First, we need to change the mechanism topology in order to skew the trajectory of point P. Then we have to ensure that the last part of the unrestricted up-squat phase

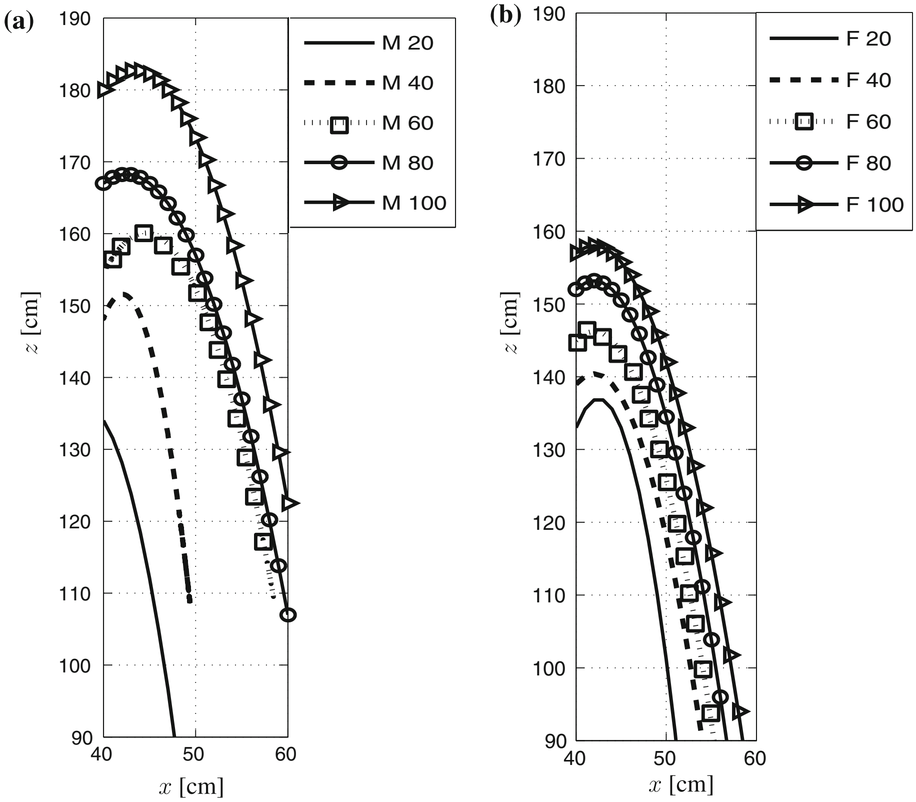

Fig. 10 Unrestricted up-squat phase analytical curves for different height percentiles: men (**a**) and women (**b**) cases

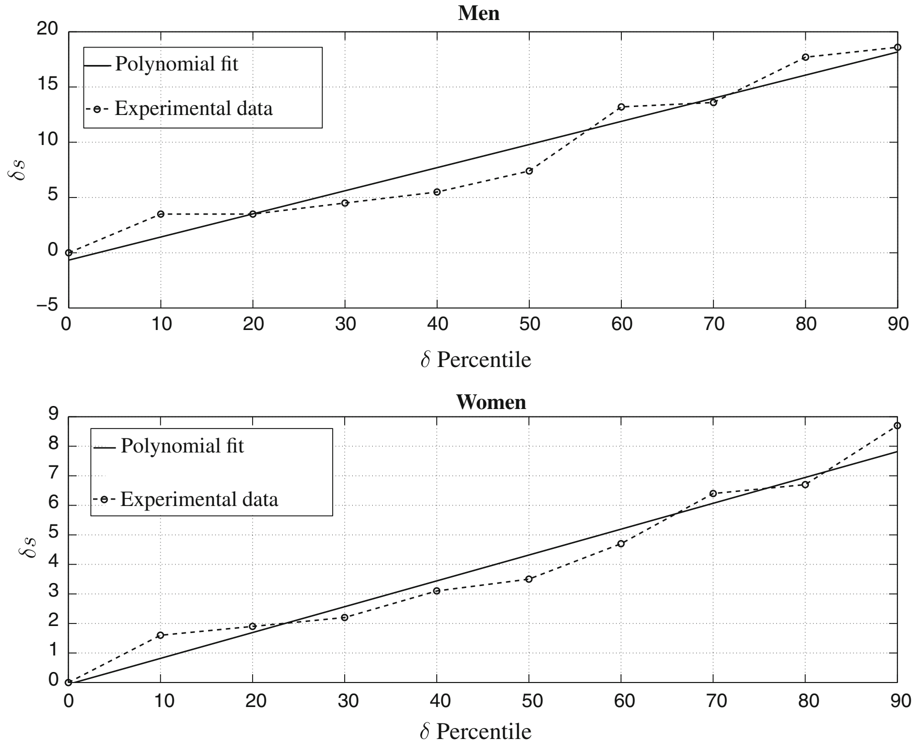

Fig. 11 Unrestricted up-squat phase analytical curves for different height percentile: men (**a**) and women (**b**) cases

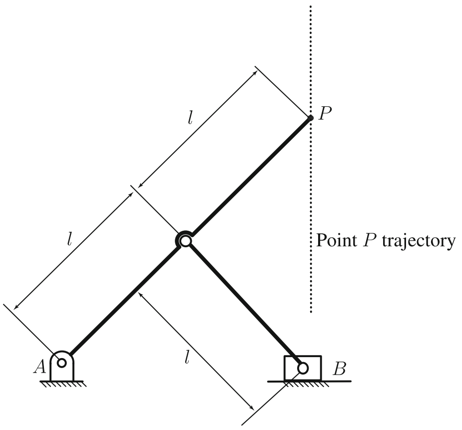

Fig. 12 Scott-Russell original mechanism

follows the analytical curves obtained through the procedure described in the previous sections.

The idea is to change the Scott-Russell mechanism going to misaligning the slider trajectory from the first fixed revolute joint A as shown in Fig. 13.

Once the general topology of the mechanism has been defined, it is possible to start with the synthesis of the dimension of the links and the misalignment of the slider. Both these values can be evaluated starting from the knowledge of the trajectory of P.

For the deduction of the closure equations of the modified mechanism we used the *constraint equations* method. A detailed description of this method is given in [24]. Here, we only report only the equations and the solution strategy.

With reference to Fig. 14, the non-linear equations for the solution of the position analysis of the mechanism are the following:

$$\{\Psi\} \equiv \left\{ \begin{array}{c} q_1 - l\cos q_3 \\ q_2 - l\sin q_3 \\ q_1 - q_4 + \frac{l}{2}\cos q_6 \\ q_2 - q_5 + \frac{l}{2}\sin q_6 \\ q_5 + \frac{l}{2}\sin q_6 - d \\ q_3 = q_3(t) \end{array} \right\} = \{0\} \tag{1}$$

where the last equation refers to the assigned motion law.

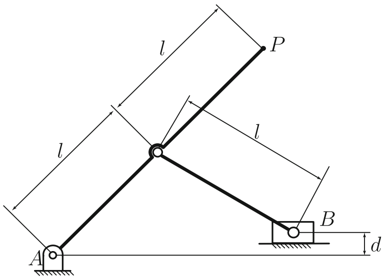

Fig. 13 Scott-Russell modified mechanism

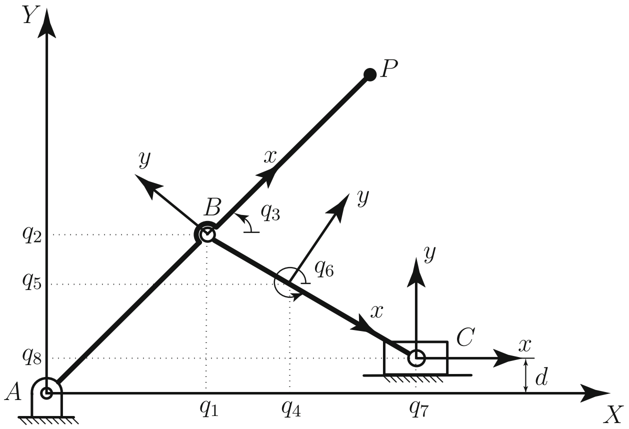

Fig. 14 Reference frames and generalized coordinates

In Eq. 1, the vector $\{q_1 \quad q_2 \cdots q_n\}^T$ is the vector of the generalized coordinates as defined in Fig. 14, while $\{\Psi\}$ is the constraint equations vector.

Our scope is to find the optimal dimensions of the mechanism. By solving the non-linear system of Eq. 1 for the vector of the generalized coordinates $\{q\}$, we can find an expression of the trajectory of the point P as a function of all the unknown parameters l and d and the driving coordinate q_3:

$$\begin{array}{l} x_p = f(l, d, q_3) \\ y_p = f(l, d, q_3) \end{array}. \tag{2}$$

Then we have created a distance function as the difference between the trajectory calculated through Eq. 2, and the experimental one:

$$\{\mathcal{D}\} = \left\{ \begin{array}{c} x_p - P_x^{\mathrm{ex}} \\ y_p - P_y^{\mathrm{ex}} \end{array} \right\}. \tag{3}$$

The problem can be solved by applying the *min-max* criteria. The scope is to find the optimal value of l and d such that the maximum value of the distance $\mathcal{D}$ is minimized.

$$MIN_{l,d}\{MAX_{l,d}\{|\mathcal{D}|\}\}. \tag{4}$$

The results of the computation produced the following optimal dimensions (see Figs. 13, 14) for the Scott-Russell mechanism:

Table 3 Optimal dimensions for the mechanism

Parameter	Value (cm)
l	35
d	35

The comparison between the curves traced by this mechanism and the experimental trajectories, shows a good agreement. In particular the difference between the two curves is lower than 4%.

5 Virtual prototyping of the mechanism

Once the mechanism has been designed and the geometry optimized, it has been possible to model the linkage by means of computer-aided engineering tools. Their application is useful for supporting the designer in building virtual prototypes in order to test the manufacturability, assembling and performance of the conceptual device. Modern CAE environments offer the possibility to perform not only the virtual modeling of the product, but also motion simulation and structural resistance verification.

The digital mock-up has been built from the results discussed in the previous sections and by means of the CAE suite Solidworks®. The device has been prototyped including structural details, locking system and user interface. The entire machine is depicted in Fig. 15.

In order to guarantee the machine to be reconfigurable in an easy way, we designed an adjustable footboard as the one shown in Fig. 16. The athlete can set the horizontal position of the footboard in function of his height according to the patterns discussed above.

Through the use of the Solidworks Motion package, a kinematic analysis has been executed in order to verify the trajectory of the barbell to be the one obtained in the previous section. In Fig. 17 the following three patterns are compared for a male 25th percentile:

- the *modified Scott-Russell trajectory*, obtained performing a kinematic analysis with the Solidworks Motion package;
- the *Experimental data*, acquired by the use of the MoCap system;
- the *numerical analysis results*, obtained performing a kinematic analysis applying the constraint equations method.

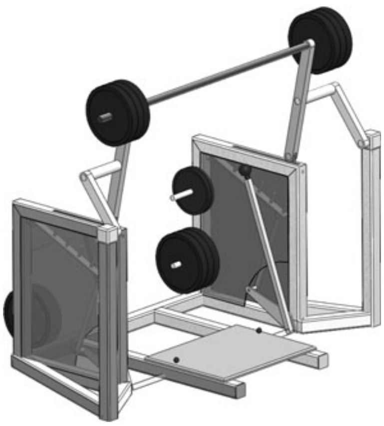

Fig. 15 CAD model of the optimized squat machine

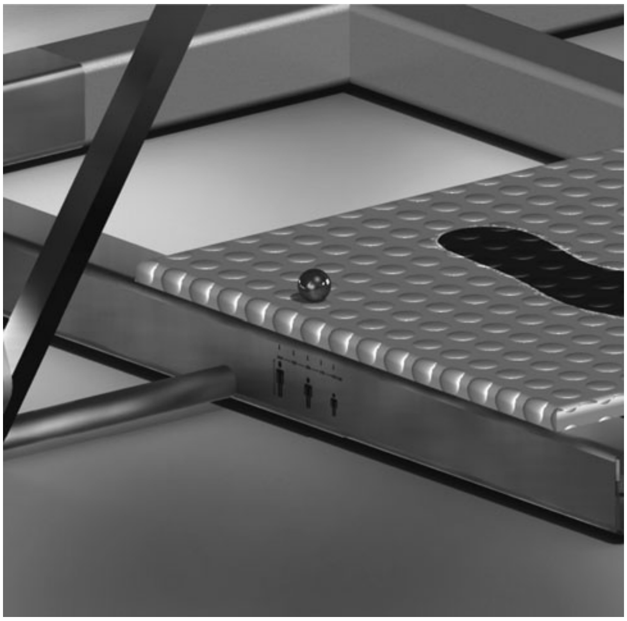

Fig. 16 A detail of the adjustable footboard

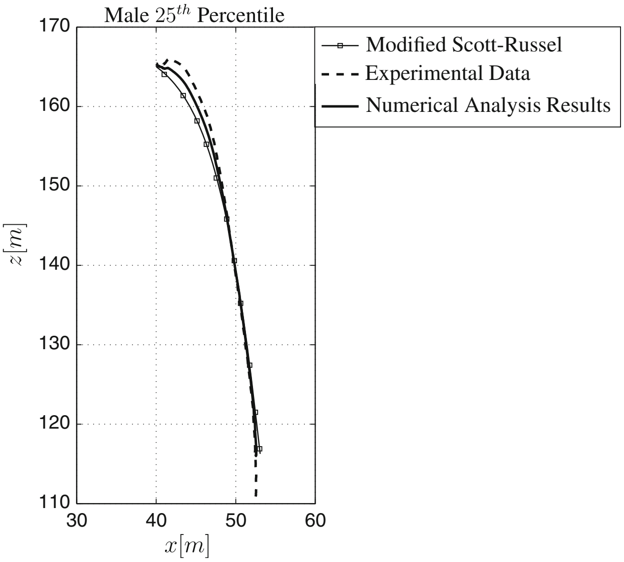

Fig. 17 Comparison among barbell trajectories: unrestricted motion versus constrained motion of the machine

As it can be noted, the designed mechanism reproduces the target trajectory with a good accuracy. The results have been also compared for different percentiles obtaining the same good accordance.

6 Conclusions

In this paper a new methodology for improving the design of a back squat machine has been presented.

Through the use of a motion capture system, experimental data on the trajectory of the barbell with no load have been acquired and processed. Results shows that this trajectory has a similar shape for all the subjects and can be approximated with a second order polynomial curve. Trajectories obtained by different athletes can be partially superimposed considering an horizontal shifting. Following this pattern, a relationship between the height percentile and the horizontal displacement of the athlete has been found, together with the optimal position in which the exercise can be executed.

All these considerations suggested using a modified straight line linkage to guide the movement of the barbell. This mechanism has been designed on the basis of the interpolated patterns and the optimal dimensions have been chosen applying the min–max criterion. Finally, through the use of CAE environment, a virtual prototype has been built and the specifications and performances of the mechanism have been verified.

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Appendix 1

Herein we report some important information on the subjects that have executed the test. Tables 4 and 5 report age, mass, height and sport background of each subject and are divided by gender. For the assessment of the sport background we chose to report a numerical index. Its range is between 0 and 5 with the following meaning:

0: any sport experience;
1: uncommon sport activity;
2: sporadic sport activity;
3: common sport activity;
4: intensive sport activity;
5: professional athlete.

Table 4 Information on the male tested subjects

Number	Age	Mass (kg)	Height (cm)	Sport background
#1	24	80	180	2
#2	30	69	169	3
#3	22	74	171	2
#4	21	75	175	1
#5	29	86	185	4
#6	28	87	194	3
#7	24	76	184	3
#8	25	78	182	3
#9	26	70	175	2
#10	31	65	168	2
#11	22	71	169	1
#12	20	72	174	3
#13	19	81	183	2
#14	23	83	182	2
#15	25	73	172	3
#16	25	68	164	4
#17	26	69	172	4
#18	35	80	176	1
#19	21	79	179	3
#20	32	80	180	2
#21	28	74	181	2
#22	24	72	182	1
#23	21	76	186	2
#24	33	88	192	3
#25	36	95	198	4
#26	38	85	181	4
#27	26	72	177	2
#28	24	98	187	2
#29	23	68	172	1
#30	22	74	180	3

Table 5 Information on the female tested subjects

Number	Age	Mass (kg)	Height (cm)	Sport background
#1	28	50	150	4
#2	24	63	165	2
#3	22	61	170	3
#4	23	67	174	2
#5	24	72	177	2
#6	28	68	180	3
#7	29	70	174	4
#8	32	62	175	1
#9	24	58	162	3
#10	25	69	161	2
#11	38	57	154	1
#12	34	52	156	3
#13	20	54	163	5
#14	19	67	167	3
#15	36	59	170	2
#16	25	68	172	2
#17	25	76	182	2
#18	25	50	156	3
#19	28	62	164	4
#20	24	64	169	2
#21	26	63	175	1
#22	23	62	170	3

Table 5 contiuned

Number	Age	Mass (kg)	Height (cm)	Sport backgroundtfgap
#23	22	72	168	3
#24	23	74	165	2
#25	24	61	172	2
#26	25	48	150	4
#27	26	62	163	1
#28	27	65	169	2
#29	28	72	176	2
#30	25	67	171	3

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