What if strength training never needed weight in the first place?

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POLITECNICO MILANO 1863

Integration of mechanical design and user experience:
a constant-force, spring based, fitness machine.

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ABSTRACT

In this thesis, I will first examine the **historical** and mechanical foundations of **strength training** equipment, with particular attention to the dominance of **mass-based resistance systems**. I will then analyse the functional and experiential limitations of **spring-based prototypes** and define the design and engineering objectives that guided the project. The core of the work will focus on the development of a **constant-force spring resistance architecture**, integrating mechanical transmission systems, **gear ratios, pulley configurations, and structural constraints** into a coherent and feasible product model.

A significant part of the development involved direct dialogue with a **spring manufacturing engineer,** through which the most suitable constant-force spring configuration was identified and slightly modified to our needs. Together, we evaluated **force curves, material properties**, durability, and scalability, addressing not only performance but also the potential for **industrial mass production**. This collaboration expanded the project beyond a conceptual exercise, grounding it in real n real life a possible future.

Furthermore, the research extended to the analysis of products and systems that employ similar resistance principles in diverse fields, including **storage mechanisms,** display systems, industrial production equipment, sports vehicles, bicycles, and fitness machines. Studying these applications allowed the identification of transferable mechanical strategies (with possible implementations) and reinforced the versatility of **constant-force systems** across different domains.

KEYWORDS

Constant-Force Springs

Resistance Exercise

Gear-Based Resistance

Strength Training Equipment

Mechanical Transmission

User-Centered Interaction

Compact Fitness Equipment

Home Gym

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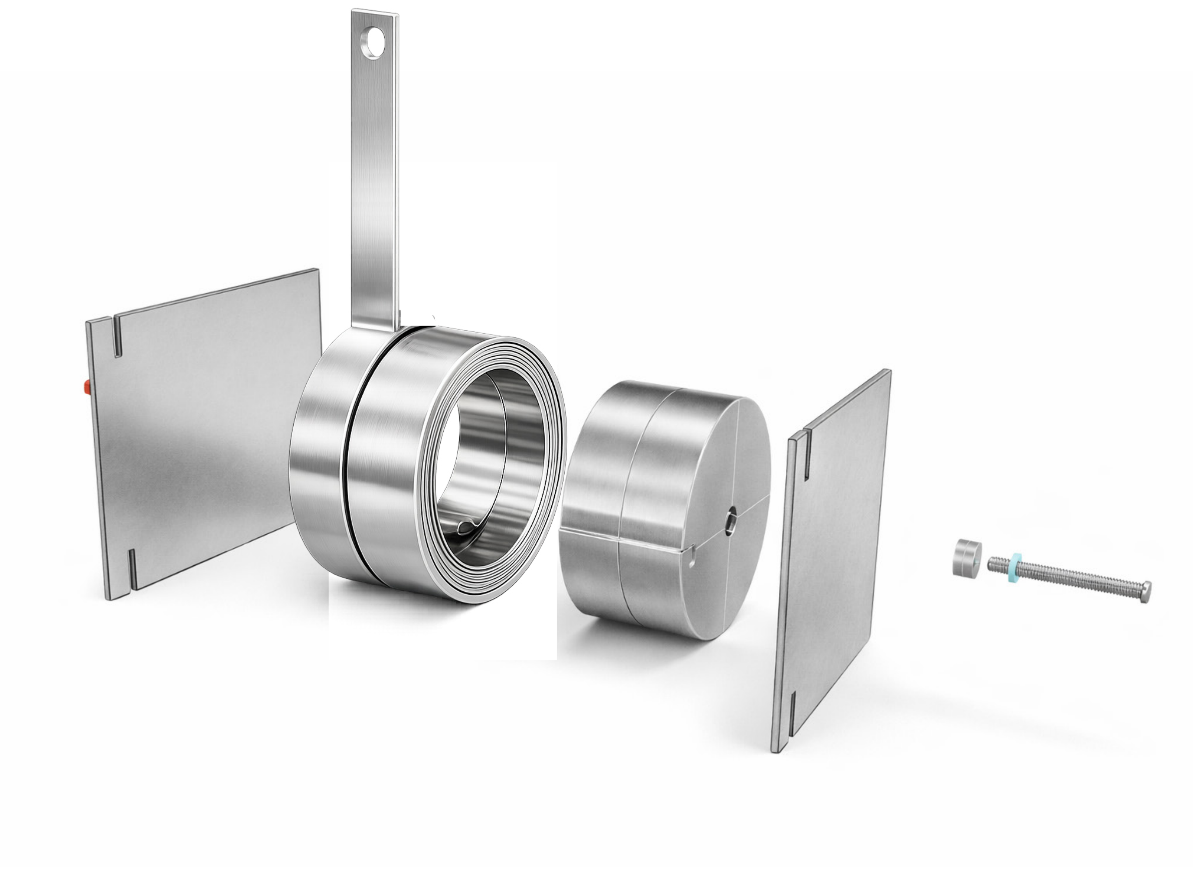
1. INTRO



This thesis develops a strength training machine using constant-force springs instead of traditional weight stacks, decoupling resistance from gravity for greater flexibility and reduced mass. The final 3D mechanical model demonstrates how design engineering bridges user interaction and mechanical complexity in fitness equipment.

CONTEXT AND MOTIVATION

This thesis proposes an **alternative approach to resistance generation** in strength training equipment, challenging the conventional reliance on mass-based systems in gym machines. Traditional cable machines operate through stacked **cast-iron weights**, where resistance depends on gravity and mass. However, muscle activation responds to resistance rather than to weight itself. Starting from this principle, the project develops a mechanically driven **fitness tower** based on constant-force springs as a substitute for traditional weight stacks.

The research evolved from an existing **spring-based prototype** that, despite its functional potential, presented critical limitations in usability. The engagement and disengagement of individual springs required physical effort and cognitive calculation, reducing accessibility and intuitiveness. The objective of this thesis was therefore twofold: to engineer a feasible and scalable resistance system based on constant-force springs, and to redesign its mechanical interface to enable immediate and **intuitive resistance selection.**

The final outcome is a fully developed 3D mechanical model integrating **modular spring packs**, a high/low **engagement mechanism**, and a gear-based transmission system inspired by flat sprocket architectures. The project investigates transmission ratios, torque distribution, pulley configurations, and dimensional constraints to ensure mechanical feasibility and structural coherence. By decoupling resistance, the system allows spatial flexibility, reduced overall mass, and a more compact architecture compared to traditional gym equipment.

Developing this project required an in-depth exploration of mechanical engineering principles that extend beyond the typical scope of a design curriculum. The need to resolve **transmission systems**, force calculations, and component sizing led to the acquisition of new technical knowledge, strengthening the integration between design thinking and engineering rigor.

This thesis demonstrates how design engineering can **bridge** user-centered interaction and mechanical complexity, reframing the concept of strength training machines through an innovative and scalable resistance strategy.

RESEARCH APPROACH

The primary objective of this thesis is to redefine the structural logic of strength training equipment by investigating alternative mechanical architectures capable of replacing traditional weight-stack systems. Rather than focusing solely on performance enhancement, the project aims to **explore how mechanical simplification,** modularity, and transmission design can generate new product typologies within the fitness industry. It also studies what is currently available in this specific field, what innovations are emerging, and what solutions could be implemented or borrowed from other **domains of knowledge.**

The weighted pack and type of resistance make this machine particularly interesting for **rehabilitation** training, because of possible movements and attachments and the very versatile resistance profiles.

As Italian designers, we value clean and **minimal mechanical solutions.** As a second objective, I tried to translate, once again, the beauty behind this design process into a tangible object, making complexity accessible, easy to understand, and intuitive to interact with. The research investigates how f**orce modulation,** transmission ratios, and resistance distribution can be embedded within a system that remains readable and user-friendly; **minimizing cognitive load** while preserving mechanical depth. However, for safety reasons, part of this complexity sometimes needs to be concealed beneath metal.

SCOPE

This thesis focuses on the architectural and mechanical redefinition of a single typology of strength training machine: **the vertical cable tower.** The scope does not include electronic integration or biomechanical performance testing, although these aspects are acknowledged as potential **future developments.**

The work concentrates on structural configuration, force transmission strategy, and user interaction mechanisms, culminating in a detailed, **production-oriented 3D model.** The outcome is intended as a flexible mechanical architecture rather than a finalized commercial product, positioning the project as a foundation for further technical refinement and industrial application.

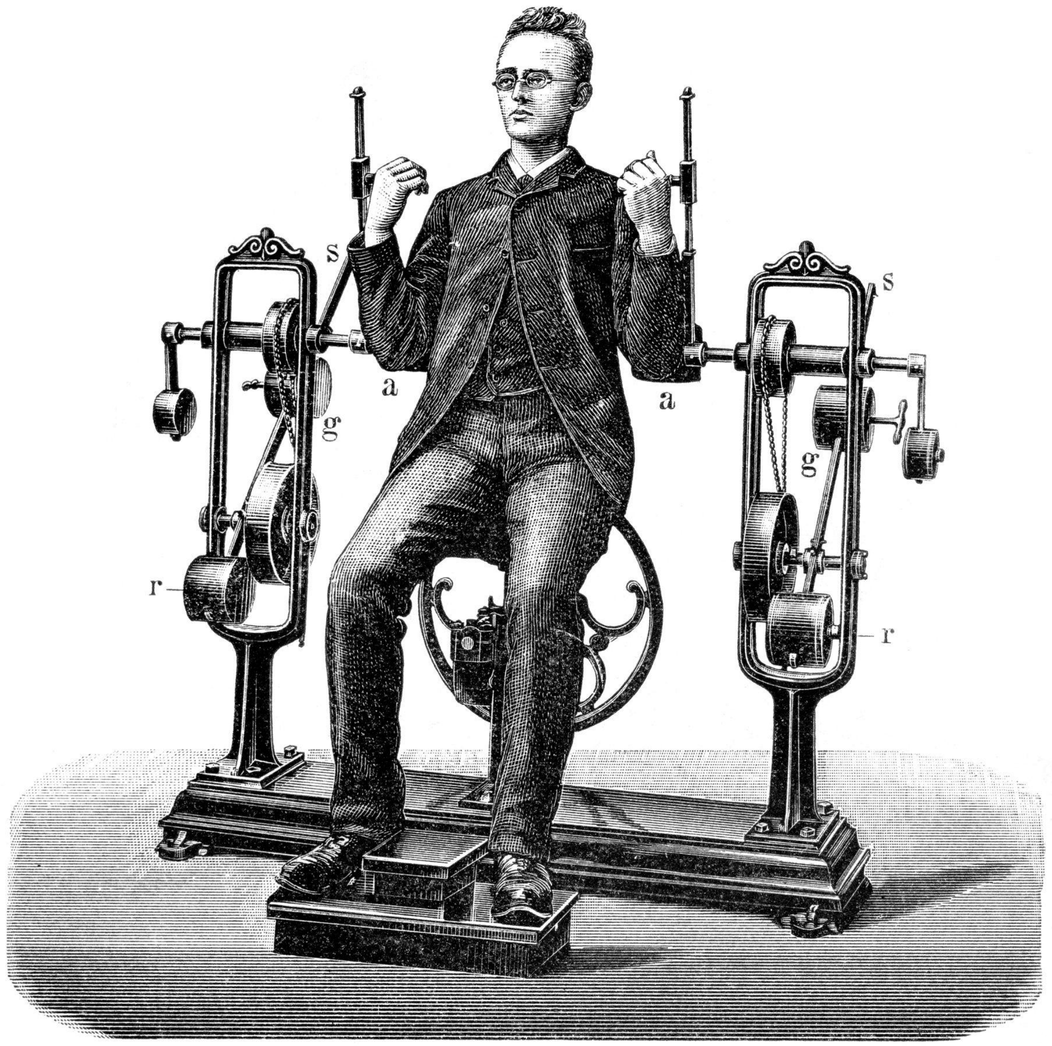
METHODOLOGICAL NOTE

The project follows a **practice-based research methodology,** in which design development and technical validation evolve simultaneously. The process combined iterative 3D modeling, dimensional studies, and consultation with industry professionals, particularly in the fields of **spring manufacturing and transmission systems.**

Design and engineering are not sequential phases. Even though, at times, one must lead the other depending on the phase or the specific technical necessity of a component, my methodology embraces a **circular workflow:** each mechanical constraint informed spatial decisions, and each architectural and interaction choice required recalculation and structural verification.

Studying how resistance systems are implemented in other industries allowed the extraction of useful principles and confirmed the cross-disciplinary nature of both the investigation and the project itself.

2. EVOLUTION OF STRENGHT TRAINING EQUIPMENT



Gustav Zander, rehabilitation machine patent 1880

The development of strength training machines has historically been driven by mechanical reliability and load scalability. However, the methods used to generate resistance vary significantly across different technologies. Understanding these systems is essential to contextualize the proposed alternative architecture developed in this thesis.

2.1 HISTORICAL DEVELOPMENT OF GYM MACHINES

The practice of physical training dates back thousands of years, with early civilisations such as the **ancient Greeks** using rudimentary forms of resistance to improve strength and **athleticism**. Athletes trained with stone or metal implements and performed **bodyweight exercises** long before formal gym environments existed.

The first systematic attempt to apply mechanical devices for physical exercise emerged in the 19th century. In the late **1850s, Swedish physician Dr. Gustav Zander** developed a series of mechanised **therapeutic machines** intended to assist movement, rehabilitation, and strength conditioning. His apparatus used weighted levers and adjustable systems to target specific muscle groups, and his concepts strongly **influenced** subsequent designs of resistance equipment.

During the 20th century, resistance training was largely dominated by free weights—barbells, dumbbells, and plates—supported by institutions such as **YMCA** and emerging bodybuilding culture. The 1960s and 1970s marked a turning point when dedicated exercise machines were introduced into **mainstream gyms**. In the late 1960s, **Arthur Jones designed the first Nautilus machines,** which featured cam-based resistance to match muscle strength curves more effectively than free weights. These innovations contributed to a widespread adoption of specialised resistance equipment and reshaped **public perceptions of strength training.**

fig.1 Nautilus cam geometry design for progressive load

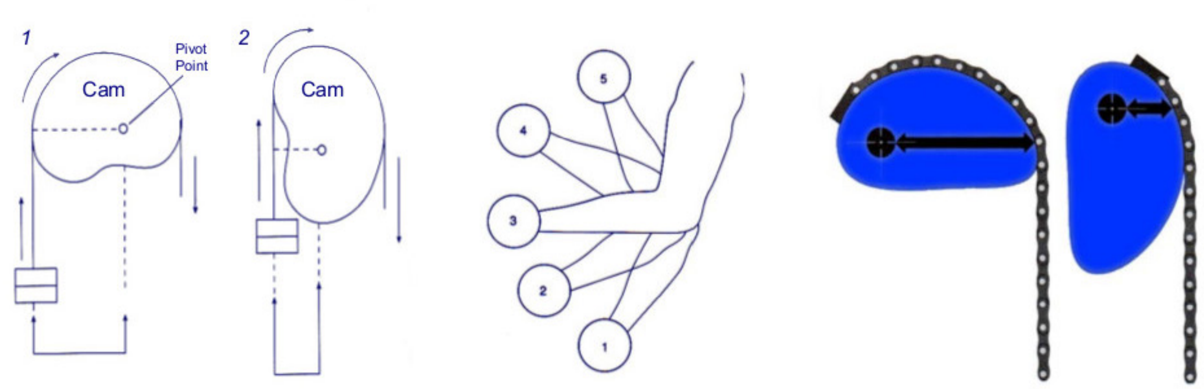


fig.2 Nautilus cam geometry and 2d simulation

An oval-shaped cam changes the effective resistance during movement by altering the lever arm distance. As it rotates, it **adjusts the load** to better match the strength curve of the exercise, providing more **uniform muscle effort** throughout the motion.

2.1 HISTORICAL DEVELOPMENT OF GYM MACHINES

The following decades saw continued diversification. By the 1970s and 1980s, both **commercial and home fitness** equipment expanded rapidly, with brands such as Total Gym and BowFlex introducing functional and versatile machines that brought **strength** training into **domestic environments.**

From the late 20th century to the present, **fitness technology** has evolved further, incorporating biomechanical insights, ergonomic refinement, and digital enhancements. **Modern equipment** ranges from traditional weight-stack machines to advanced systems that integrate smart feedback, pneumatic resistance, and biomechanical optimisation. This long trajectory reflects a **continuous effort** to improve both the efficacy and accessibility of strength training tools for users of varying goals and abilities.

Beyond the evolution of machine geometries, configurations, and training objectives, the debate today increasingly concerns the very **origin of resistance that generates the exercise stimulus. Different technologies** propose alternative ways of producing force, and multiple systems currently coexist and compete on the market. Elastic bands, pneumatic cylinders, hydraulic circuits, magnetic brakes, and traditional iron weights each embody distinct mechanical principles and training implications. **The following section analyses the most established resistance systems**, comparing their operational logic, advantages, and limitations in order to frame the position of this research within the contemporary landscape.

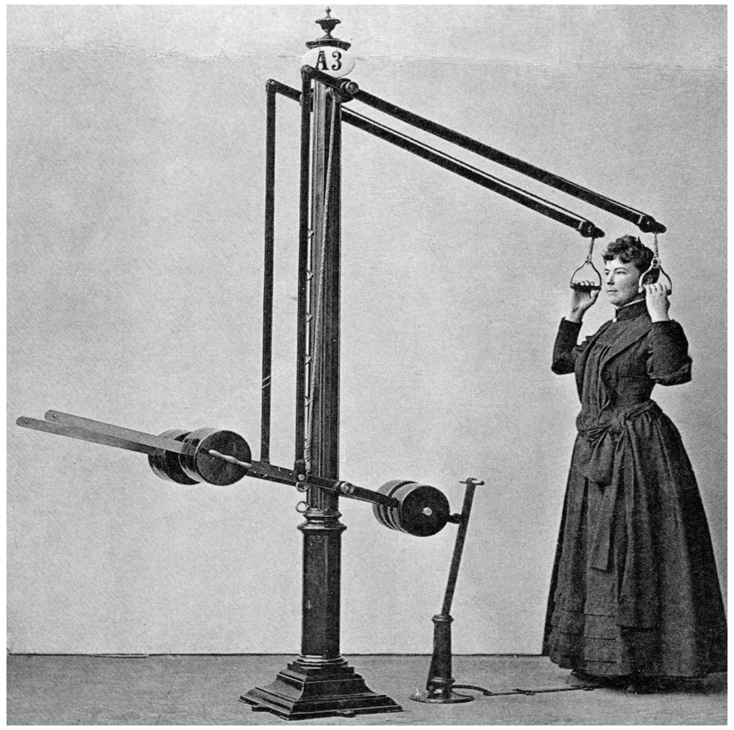


fig.4 Zander machine 1850

fig.5 Catalogo per attrezzi domestici 1990

2.2 COMPARATIVE ANALYSIS OF RE-SISTANCE SYSTEMS

CAST IRON

Traditional selectorized machines rely on vertically **stacked cast-iron** plates connected through cables and pulleys. Resistance is selected via a mechanical pin that engages a defined number of plates. The system is entirely **gravity-dependent** and requires vertical orientation. This system remains dominant in commercial gyms but is **less suited for compact or domestic environments.** Iron weights are highly praised in the bodybuilding community because they represent old-school tradition, raw strength, and the authentic essence of training. **The metallic "clang"** when the plates collide creates a powerful psychological boost and evokes the golden era of classic gyms and icons like Arnold Schwarzenegger. The phrase "pumping iron" popularized by the documentary **Pumping Iron** literally means lifting weights, but it also symbolizes the intense, gritty lifestyle and mindset of serious bodybuilding. Iron isn't just a material it's a symbol of discipline, intensity, and hardcore lifting culture.

ADVANTAGES

- Mechanical simplicity and durability
- Clear and intuitive load selection
- High maximum resistance capacity
- Established user familiarity

LIMITATIONS

- Heavy and bulky structure
-Transport and installation complexity
- Dependency on gravity
- Large spatial footprint
- CO2 emissions (high lesting time
- High material consumption

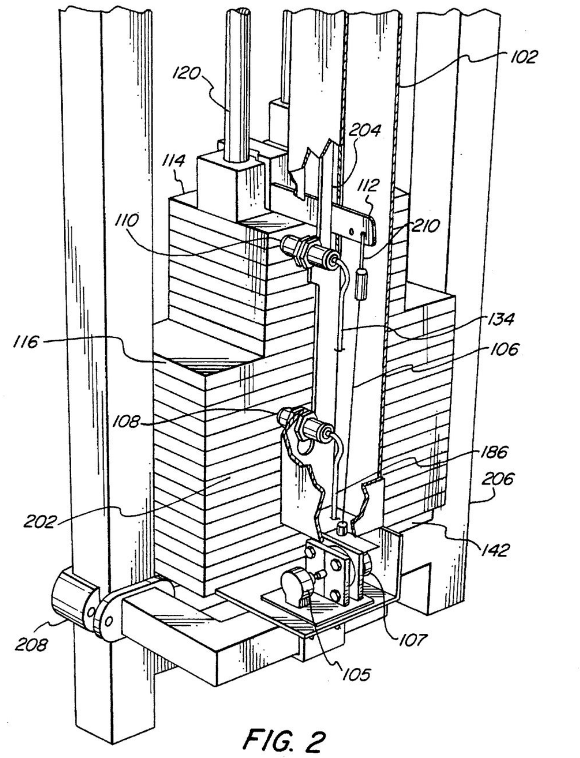


FIG. 2

fig. 6 Patented on stackable iron wighted machine

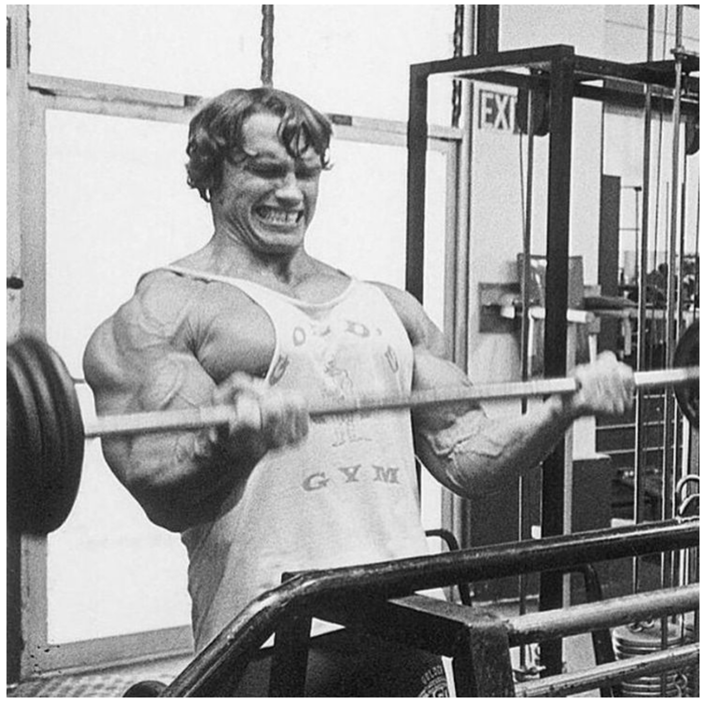


fig. 7 Arnold training with iron weights at gold's gym

WATER

Water-based resistance is a mechanical system that uses the **physical properties of water** mainly **drag and inertia to create load.** It is most commonly applied in rowing machines, where paddles or impellers spin inside a sealed water tank. When you pull, the blades accelerate the water; **the faster you pull, the greater the drag force** generated. This makes the resistance speed-dependent, meaning the user naturally controls the intensity through effort rather than selecting a fixed weight.

One distinctive characteristic of water resistance is the **higher initial resistance** at the start of the movement. At the beginning of the stroke, you must overcome the inertia of still water (its mass at rest). This creates a heavier, more pronounced "catch" phase, very similar to the feeling of rowing an actual boat in water. Once the water is moving, **resistance becomes smoother** and proportional to stroke power.

The main applications of this system are: **Rowing machines** endurance training), pro ski ergometers and soem rehabilitation/ low-impact cardio devices

fig. 8 Water Rower machine

ADVANTAGES

- Realistic feel: Water creates a smooth, continuous resistance that closely mimics real rowing, feeling more natural than magnetic or weight-based systems.

- Self-regulating intensity (natural force curve): The harder and faster you pull, the more resistance you generate

- Joint-friendly: The fluid resistance reduces sudden uncontrolled stress on joints.

- Low mechanical complexity

LIMITATIONS

- No fixed resistance levels

- Limited applicability

- Bad for controlled strength develop

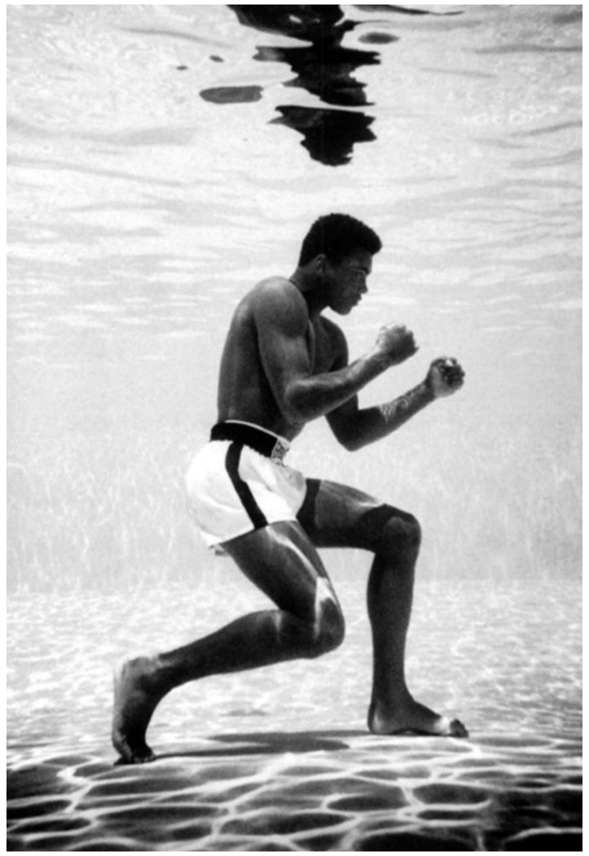


fig. 9 Muhammed ali trining under water

fig. 10 Water Rower machine detail

AIR RESISTANCE

Air resistance machines work through a **flywheel equipped with fan blades that rotate inside a housing**. When the user pulls or pushes (through a belt, chain, or direct linkage), the flywheel spins and the blades move air. The resistance is generated by **aerodynamic drag:** the faster the blades rotate, the more air they displace, and the greater the opposing force.

Unlike weight stacks or elastic systems, the **resistance** does not **depend** on position, but on **speed** of movement. If you move slowly, resistance is low. If you accelerate aggressively, resistance increases dramatically. This creates what is called a velocity-dependent resistance profile.

Key components of this system:

- Flywheel mass and diameter - determine rotational inertia and smoothness of motion

- **Blade geometry** (surface area, pitch, curvature) - influence how much air is displaced and how progressive the resistance feels

- Air housing and vents - control airflow entry and exit, affecting both resistance behavior and noise

- Transmission system (chain, belt, strap) - converts linear pulling force into rotational torque

The system is **mechanically simple**: there are no heavy plates, cams, or friction brakes. Resistance is generated purely by moving air, which reduces internal wear compared to friction-based systems. However, turbulence inside the housing produces noticeable **noise**.

fig. 11 Assault's air resistance cycle machine

Concept2 Rowers:

These machines use a chain-driven flywheel and include adjustable **dampers that modify how much air** can enter the housing, slightly altering the feel of resistance while maintaining the same velocity-dependent principle.

Assault Fitness AirBikes:

Air bikes combine a large fan flywheel with moving handles, engaging both upper and lower body. Because resistance scales with speed, they allow extremely high power outputs without needing heavy mechanical loads.

ADVANTAGES

- Infinite scaling of resistance
- Lightweight construction
- Suitable for high-intensity training

LIMITATIONS

- No constant resistance
- Noisy
- Bad for slow, controlled movements

fig. 12 Concept2Rowers air resistance rowing machine

fig. 13 Assault's air resistance cycle machine 2

PNEUMATIC/AIR COMPRESSED SYSTEM

These systems generate resistance using **compressed air cylinders,** where the load is adjusted by modifying the internal air pressure. Instead of lifting a physical mass, the user works against the force produced by pressurized **air acting on a piston**.
A pneumatic resistance machine typically includes:

- Air cylinder (piston + chamber) - converts **linear motion into pressure**-based resistance

- **Pressure regulation system** - adjusts internal pressure to set the load

- Valves and flow control units - manage air transfer between chambers

- Structural frame and linkage - transmit user force to the piston rod

When the user applies force, the piston compresses the air inside the chamber. The **higher the preset internal pressure**, the greater the **opposing force.** Unlike other systems, resistance here remains relatively constant throughout the stroke.

Because there is **no heavy** mass being accelerated, pneumatic systems eliminate rotational inertia and offer a very linear and smooth resistance profile. This makes them particularly interesting for **rehabilitation** and controlled strength work.

However, air compression introduces thermodynamic effects: during rapid repetitions, air temperature can increase slightly, potentially affecting internal pressure consistency. **High-end** systems compensate for this through pressure regulation technology.

ADVANTAGES

- Smooth and precise resistance - very fluid movement pattern

- Reduced mechanical wear - fewer friction-based components

- Lower overall machine weight - no weight stacks required

- Compact unit - suitable for modular designs

- Possible active resistance in the negative range on motion

LIMITATIONS

- High production cost - precision cylinders, valves, and regulators are expensive

- Need for pressure systems - integrated compressor or external air supply required

- Maintenance complexity - seals, valves, and pressure lines require periodic inspection

- Potential air leakage over time

fig. 14 Kaiser pneumatic compressed air quad machine

MAGNETIC RESISTANCE SYSTEM

Magnetic systems generate resistance through eddy **currents** created between magnets and a metallic flywheel. When the **flywheel rotates inside a magnetic** field, currents are induced in the **metal, producing an opposing torque** — without physical contact.

There are no friction pads or airflow systems: resistance comes from electromagnetic interaction, which makes the movement very smooth and quiet.

From an engineering perspective, the system includes:

- Alluminum flywheel

- Magnet assembly

- Adjustment mechanism (magnet distance or field intensity)

- Transmission system or chain

Resistance increases with rotational speed, but in a more controlled and linear way compared to air systems.

Peloton uses adjustable magnetic braking to provide smooth and quiet resistance transitions.

Gym Monster combines magnetic and motor-controlled resistance in a compact digital strength system, enabling electronically regulated loads without traditional weight stacks.

Technogym integrates magnetic resistance in high-end cardio machines, allowing precise and silent load control.

ADVANTAGES

- Silent operation

- Low maintenance (no friction wear)

- Smooth and progressive adjustment

- Compact and durable design

- Cardio and controlled resistance training

LIMITATIONS

- Primarily rotational applications

- Limited max force compared to weight stacks

- Low torque at very slow speeds

- Requires electronics for precise control

- Not suited for high-load strength applications.

fig. 15 Peloton magnetic resistance bycicle

LINEAR SPRING SYSTEM (PILATES)

Reformer machine

Pilates reformers use **extension springs** to generate resistance. As the carriage moves and the springs elongate, the **force increases progressively.** This means the load grows along the movement path, rather than remaining constant.

The system is mechanically simple and consists of:

- Extension springs with calibrated stiffness

- Sliding carriage on linear rails

- Anchor points to combine multiple springs

- Optional cables and pulleys

Resistance depends on how **much the springs stretches :** the beginning of the movement feels lighter, while the end range becomes more demanding. This progressive force curve makes the system suitable for **controlled exercises rehabilitation.**

ADVANTAGES

- Lightweight and modular structure

- Compact design

- Simple and reliable mechanics

LIMITATIONS

- Progressive (non-constant) resistance

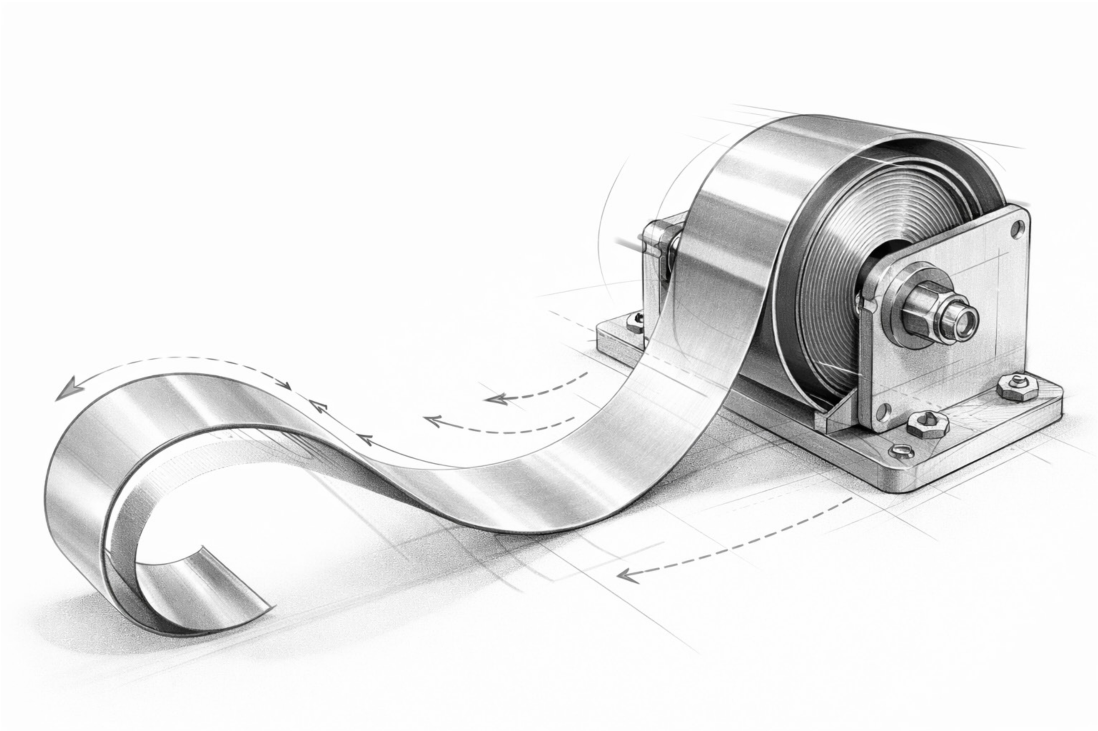
- Limited maximum load compared to traditional strength machines

- Spring fatigue over long-term use

fig. 16 Reformer machine

fig. 17 Reformer's resistance spirngs profile

3. CONSTANT-FORCE SPRINGS AND INDUSTRIAL APPLICATIONS



A constant-force spring is a type of spring that — unlike traditional extension or compression springs — provides nearly the same force over its entire travel length, rather than increasing resistance as it stretches. In other words, it breaks the usual "Hooke's Law" behaviour where force rises proportionally with extension.

3.1 FOUNDAMENTALS OF SPRINGS MECHANICS

Mechanically, these springs are made from a **tightly coiled strip** of spring steel or similar material. As the spring unrolls during use, only a small portion of the material near the roll contributes to the force. Because the geometry in that bending region doesn't change much as the spring uncoils, the **resisting force stays nearly constant** rather than rising sharply.

This results in a flat force-vs-displacement profile, which is fundamentally different from conventional springs and very valuable in controlled resistance applications.

Why Constant-Force Mechanics Make Sense for Gym Equipment ?

- In strength and conditioning, **pure constant force provides several important benefits**:

True Constant Resistance

With most traditional resistance systems (air, water and progressive springs), the applied force changes during the exercise range. With constant-force springs, the muscular effort required stays the same from start to finish, which better targets muscle tension throughout the full motion. This can **improve muscular engagement**, control, and training specificity, particularly for strength and hypertrophy work. This **consistent load delivery** is precisely the reason these springs are prized in industrial applications where a predictable force is essential.

Smooth, Controlled Motion

Because the spring force doesn't spike or dip, user movement is **smooth and predictable** — no sudden changes in tension or unexpected force peaks. This reduces the chance of jerks or **overstressing joints(no)** which is especially beneficial for beginners, rehabilitation clients, or anyone training slow and controlled reps.

fig. 18 Constant force springs real/sketch

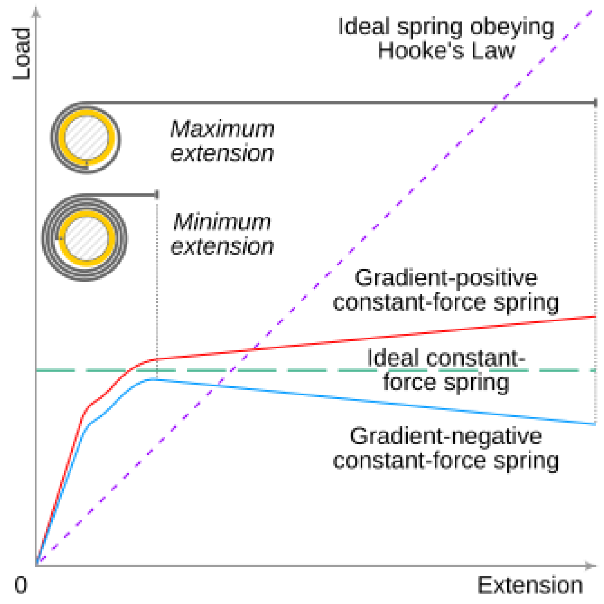


fig. 19 How CFS behave compared to normal soprings

3.1 FOUNDAMENTALS OF SPRINGS MECHANICS

Reduced Wear and Higher Reliability

Constant-force springs **distribute load evenly** throughout the travel range, which reduces localized stress on components. In industrial settings, this leads to less mechanical wear and longer lifetimes. The same principle applies in gym machines: parts under constant load tend to age more uniformly and reliably than those under variable stress.

Compact, High-Force Design

Despite their relatively small size, constant-force springs can deliver **significant forces** and long travel lengths. This allows gym equipment to have high resistance in a compact footprint, ideal for home or commercial units where space and weight are critical.

Precision and Customization

The force level of these springs is determined by **material properties** and coil geometry, meaning engineers can design equipment with exact and reproducible resistance levels that match specific training goals.

The system is **purely mechanical,** avoiding compressors, electronics, or heavy weight stacks, which makes it **compact**, **lightweight**, and reliable. Additionally, the smooth and evenly distributed load reduces mechanical wear, resulting in lower maintenance and longer equipment lifespan.

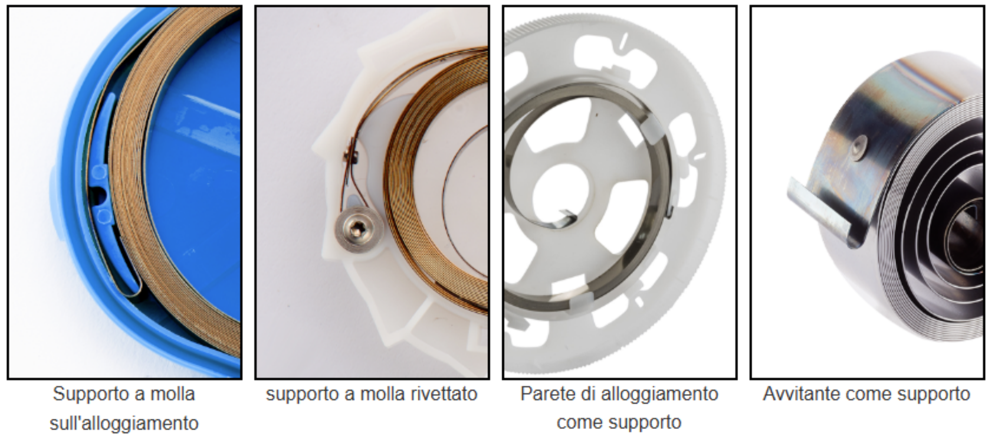


fig. 20 locking systems of the pre tension

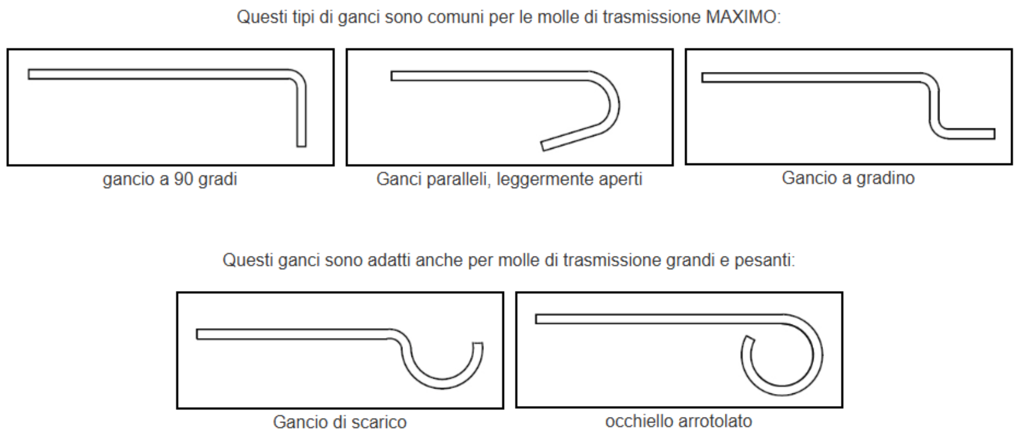


fig. 21 ending profiles of the locking part of CFS

3.2 PRODUCTION AND APPLICATIONS

Constant-force springs are **highly engineered** mechanical components designed to deliver nearly uniform force over a defined travel length. Unlike traditional extension springs governed strictly by **Hooke's Law**, these springs are manufactured from pre-stressed strip material that is tightly wound onto a drum. During operation, the strip uncoils while maintaining an almost constant restoring force, determined primarily by material properties, strip thickness, radius of curvature, and residual stress introduced during forming.

Engineering Characteristics and Design Calculations

Key parameters include:

- Material (high-carbon, steel or stainless steel)
- Strip thickness and width
- Inner and outer coil diameter
- Number of wraps on the drum
- Effective usable length
- Stress distribution during bending and uncoiling

The force generated by the spring is largely defined by **strip thickness** and material modulus, while fatigue life depends heavily on stress amplitude and the curvature imposed during winding.

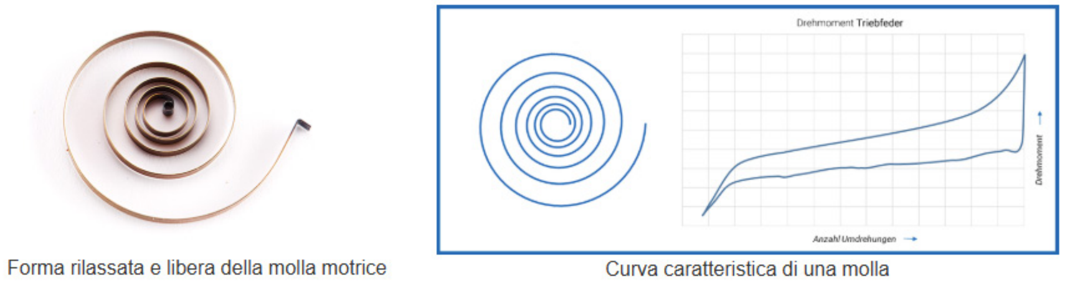


fig. 22 relaxed CFS with no cage and the exact constant patch

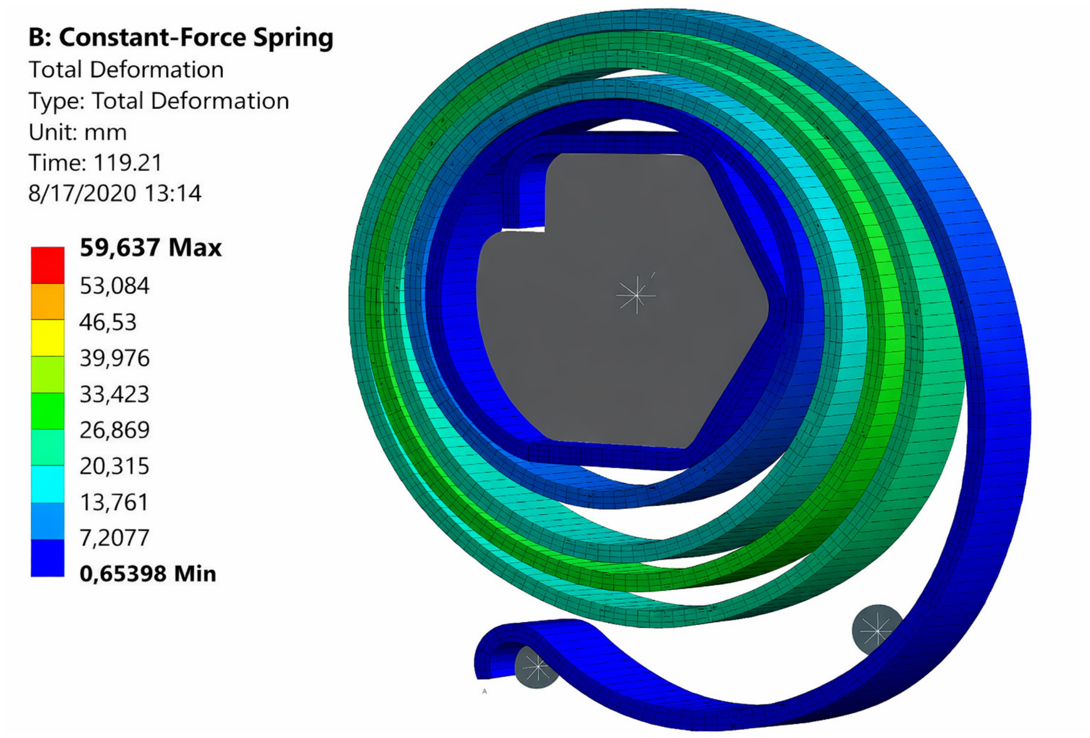


fig. 23 FEA of deformation of CFS under tension

3.2 PRODUCTION AND APPLICATIONS

Typical Industrial Applications

Constant-force springs are already **widely used** wherever a consistent mechanical force is required over a range of movement — which reinforces why they're suitable for gym equipment:

Counterbalancing (door closers, window regulators, lids) — forces remain uniform as objects move.

Cable retractors and hose retrievers — tension stays consistent even as cable length changes.

Tool returns and mechanical linkages — predictability is key.

Appliances and consumer devices (hair dryers, chairs, mechanisms requiring smooth resistance).

Aerospace and automotive (seat belts, window regulators, deployable structures) — reliable force throughout motion is important for safety.

Industrial automation and robotics — smooth, constant biasing forces improve system stability.

These applications highlight the versatility and mechanical robustness of constant-force spring systems — and suggest a strong rationale for bringing them into fitness equipment design.

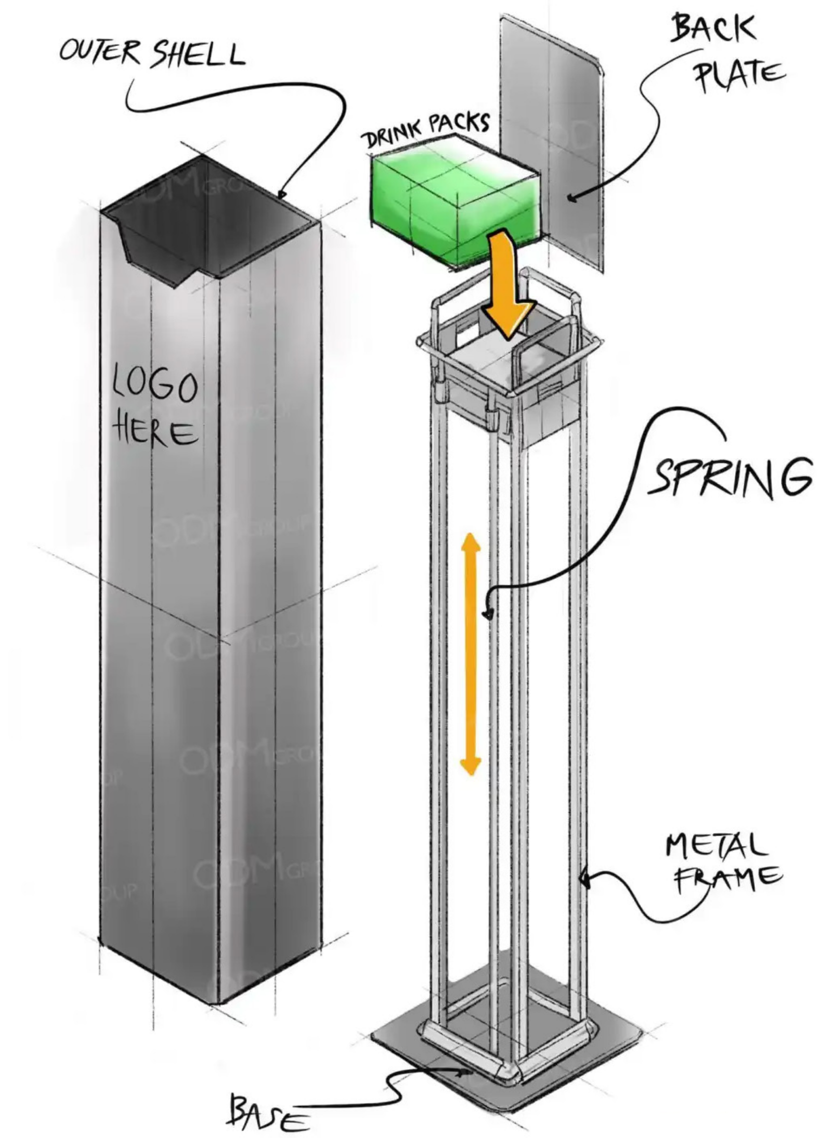


fig. 24 Scheme of CFS loaded display/dispenser

3.3 COLLABORATION WITH SPRING MANUFACTURERS

Thanks to engineer **Luigi Grassi,** the original inventor of the machine concept (patent pending), we established direct contact with ***Kern-Liebers,*** a leading German spring manufacturer. Through multiple technical meetings and calls with e**ngineer Franco C**. we conducted a comparative analysis of different spring categories (Transmission springs, Roller (constant-force) springs, Spiral springs, Power springs)

After e**valuating mechanical efficiency**, compactness, force profile, and integration feasibility, we determined that roller-type constant-force springs were the most suitable solution for our machine.

The primary technical constraints were:

Dimensional limitations
The springs needed to fit inside a very narrow vertical tower structure.

Life cycle requirements
Standard catalog values did not initially meet our expected durability targets.

We carefully analyzed and adjusted several parameters:

Strip thickness, Internal and external coil diameters, Material selection, Surface treatments, Usable spring length, Number of preloaded wraps (before usable lenght)

By iterating these variables with Kern-Liebers engineer Franco C. we developed a **customized configuration inspired by the SR78** spring, but modified to better suit our structural and durability needs.

Final Outcome

Through optimization of geometry and stress distribution, we achieved:

Approximately 30,000 life cycles, this was the toughest challenge, we had to play around a lot with thickness, Int. and Ext. diameter etc... to make the spring have a move generous roll --> extend its life span. (while maintaining compact integration within the tower system)

This process demonstrated that constant-force springs are not merely catalog components but **highly tunable mechanical** systems. By adjusting key design parameters in collaboration with an experienced manufacturer, we were able to tailor the spring precisely to the functional and spatial constraints of the fitness machine.

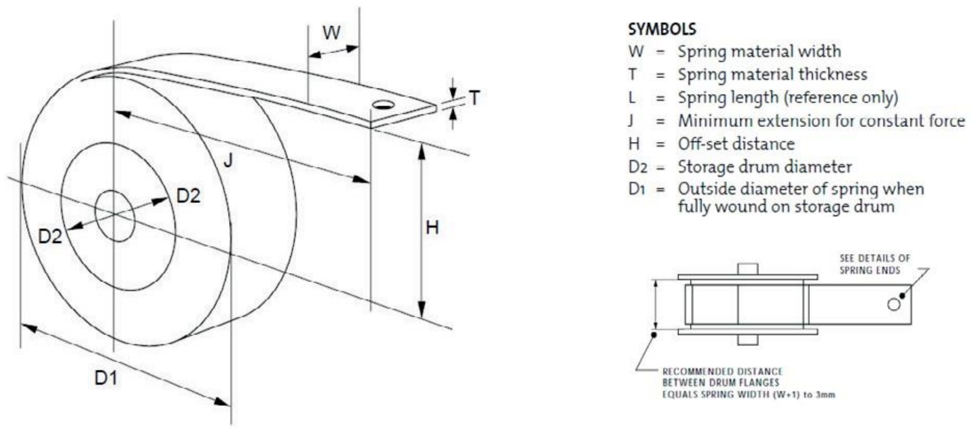


fig. 25 The main variables of a CFS

KERN LIEBERS

STANDARD RANGE
EXTENSION SPRINGS

LOAD +/- 10%		EXTEN-SION mm	MATERIAL			D2	D1	H	J	I/D*	SPRING	SPRING	Average Fatigue Life Cycles
Newtons	Kg/F		W	T	L	mm	mm	mm	mm	spring mm	ENDS	No.	
59,8	6,1	1340	51	0,4	1600	46	55	40	69	39	F	SR49	15000
70,6	7,2	2100	38	0,64	2500	73	86	62	108	60	G	SR50	15000
82,7	8,4	1850	51	0,56	2200	64	76	54	95	53	K	SR51	15000
93,8	9,6	2100	51	0,64	2500	73	86	62	108	60	K	SR52	15000
0,26	0,03	150	3	0,05	200	8	9	6	11	7	E	SR53	40000
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2,6	0,26	390	13	0,13	500	20	22	16	27	17	D	SR60	40000
3,1	0,32	460	13	0,15	600	24	26	19	33	20	A	SR61	40000
3,9	0,40	460	16	0,15	600	24	26	19	33	20	A	SR62	40000
4,7	0,48	620	14	0,2	800	32	35	25	44	27	A	SR63	40000
6,5	0,67	770	16	0,26	1000	40	44	32	55	34	A	SR64	40000
7,8	0,80	770	19	0,26	1000	40	44	32	55	34	A	SR65	40000
9,3	0,95	930	19	0,3	1200	48	53	38	66	40	A	SR66	40000
10,9	1,10	1085	19	0,35	1400	56	62	44	77	47	A	SR67	40000
12,5	1,3	930	25	0,3	1200	48	53	38	66	40	C	SR68	40000
14,5	1,5	1085	25	0,35	1400	56	62	44	77	47	C	SR69	40000
16,6	1,7	1200	25	0,4	1600	64	71	50	88	53	C	SR70	40000
18,6	1,9	1400	25	0,46	1800	72	80	57	100	60	C	SR71	40000
21,8	2,2	1085	38	0,35	1400	56	62	44	77	47	F	SR72	40000
25	2,5	930	51	0,3	1200	48	53	38	66	40	F	SR73	40000
28	2,9	1400	38	0,46	1800	72	80	57	100	60	F	SR74	40000
33,2	3,4	1200	51	0,4	1600	64	71	50	88	53	F	SR75	40000
39	4	1950	38	0,64	2500	101	111	79	138	84	G	SR76	40000
46	4,7	1400	51	0,56	2200	88	97	69	122	73	K	[illegible]	40000
52	5,3	1800	51	0,64	2500	101	111	79	138	84	K	SR78	40000

52	5,3	1800	51	0,64	2500	101	111	79	138	84	K	SR78	40000

fig. 26 the chosen spring from the catalogue

STANDARD RANGE
EXTENSION SPRINGS

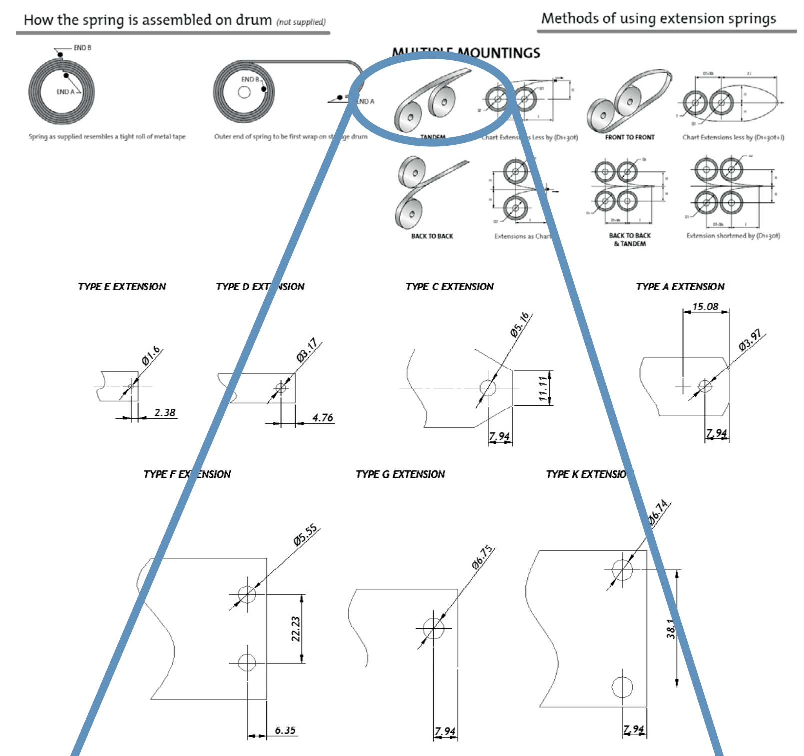


fig. 27 possible configurations of CFS

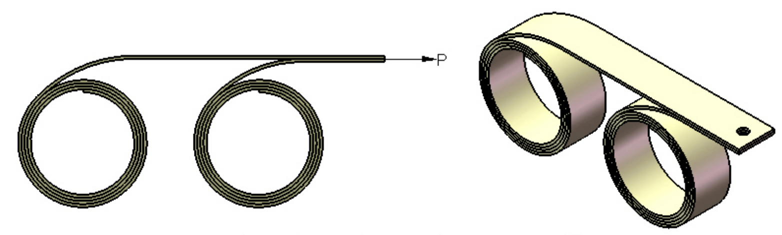
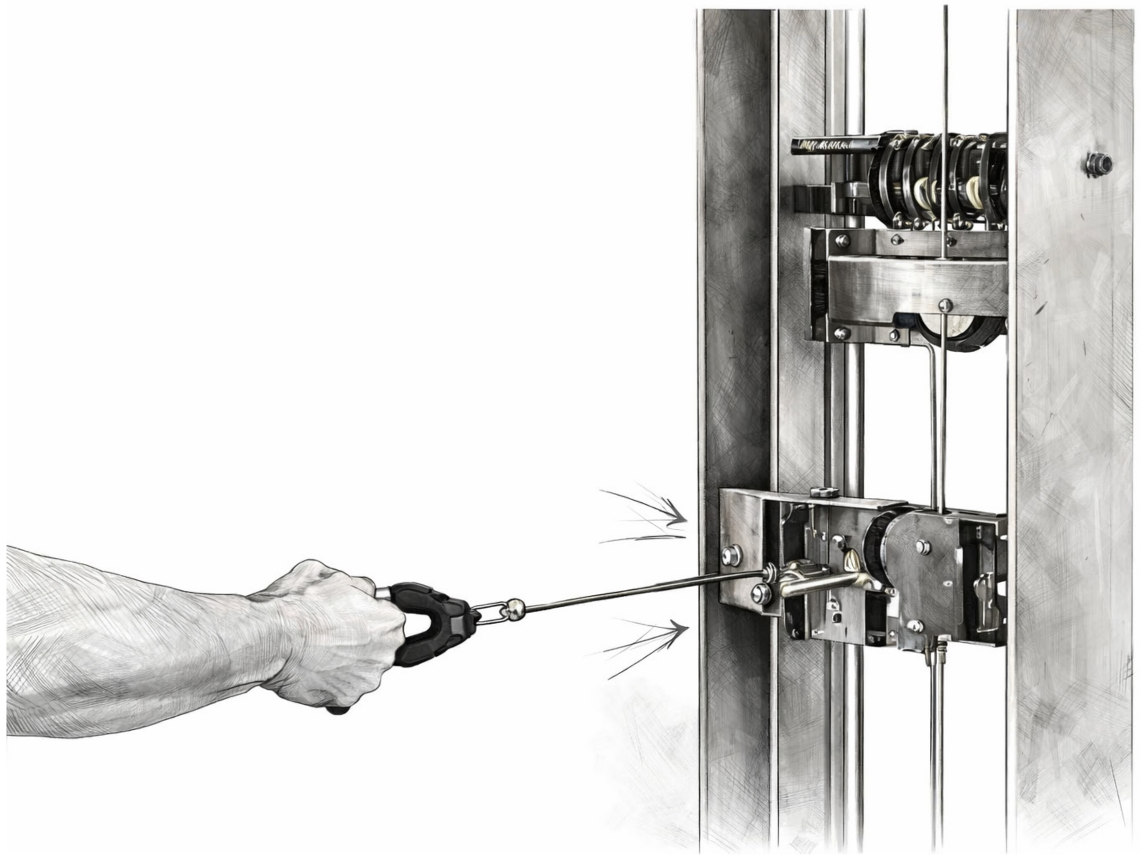


fig. 28 Tandem configuration a double spring

4. DESIGN PROCESS



This chapter examines the initial prototype developed by engineer Luigi Grassi, highlighting its functional strengths and structural limitations. While the constant-force system proved mechanically effective, issues emerged in spring integration, transmission efficiency, and load adjustment usability. The lack of a safe and intuitive resistance selection system revealed important ergonomic gaps. These insights guided the transition toward a more user-centered and refined redesign.

4.1 INITIAL PROTOTYPE & LIMITATIONS

The development of this project began with an in-depth analysis of the **initial prototype** conceived by engineer Luigi Grassi. Before proposing any modification, it was essential to fully understand the mechanical logic, construction principles, and functional philosophy behind the original machine.

A factory visit played a crucial role in this phase. Together with Luigi, we **physically assembled the prototype.** This hands-on experience was fundamental: beyond technical drawings or conceptual explanations, physically mounting each component allowed me to understand the mechanical relationships, tolerances, assembly constraints, and real-world behavior of the system.

Structural and Functional Overview of the Prototype

Although rudimentary in appearance, the prototype already embodied the essential functional **principles of the machine.**

The structure:

- Two vertical sliding carriages that allowed height adjustment of the pulling point for different exercises

- A spring pack system located inside the tower

- A rear structural plate intended to connect and tension multiple constant-force springs

- A pulley system that provided a 2:1 mechanical advantage, effectively halving the perceived resistance

From a purely functional perspective, the machine worked. The constant-force springs provided consistent resistance, and the carriage system allowed adjustable pulling height. However, **several limitations** became evident during assembly and testing.

fig. 29 The actual prototype of the first machine

4.1 INITIAL PROTOTYPE & LIMITATIONS

Spring Integration and Stability:

The **rear plate** responsible for connecting the spring packs was not yet structurally optimized. It lacked clear path, added unnecessary weight, and did not efficiently distribute loads. This affected both stability and compactness.

Pulley-Based Transmission System:

The initial configuration relied **heavily on multiple pulleys.** While functional, this introduced friction losses, alignment sensitivity, possible difficulties in cable path and mechanical complexity. In later development stages, this approach was **reconsidered** in favor of a **transmission system** with no pulleys and gear-based mechanical reduction, improving efficiency while preserving spring resistance integrity.

Weight Adjustment Mechanism (Major Critical Point)

The most significant limitation was the **absence of a simple, safe**, and intuitive method to **change resistance** during use.

- Adjusting load required accessing internal components.
- It was necessary to **manually engage or replace springs**.
- The process was neither ergonomic **non user-friendly.**
- Safety concerns arose due to direct interaction with internal spring elements under tension.

This design was mechanically viable but not aligned with modern user expectations in terms of usability, safety, and immediacy.

Ergonomic and **User-Centered Gaps**

The user experience required **frictionless interaction**, especially regarding load variation a fundamental aspect of strength training, that coudnt be solved with phisically switching springs every time.

Possible direction:

My primary objective moving forward was to reinterpret the machine through a **user-first approach**. While respecting the original mechanical vision, the focus shifted toward:

Maximizing operational **safety**

Simplifying resistance **adjustment**

Resistance profile selection

Enhancing overall efficency

In particular, **resistance variation** needed to become **intuitive**, accessible, and safe — ideally achievable without exposing internal components or interrupting the exercise flow. The goal was to eliminate cognitive and physical friction for the user, ensuring that the UX remained seamless.

This initial analytical phase was essential. By physically engaging with the prototype, identifying structural and ergonomic weaknesses, and understanding its mechanical strengths, it became possible to define a clear direction for redesign. Rather than starting from scratch, the process evolved from a critical evaluation of what already worked and what required fundamental rethinking.

The insights gained from this stage laid the foundation for the subsequent phase: the conceptual redesign and integration of new mechanical solutions aimed at transforming a functional prototype into a refined, user-oriented training machine.

4.2 DESIGN PROCESS (sketches; CAD development)

First concept: Early Sketches and Preliminary 3D Models

This phase of the project marks the transition from **analytical** research to conceptual exploration. After identifying the limitations of the initial prototype, the development process moved into a more experimental stage, focused on imagining new geometries, testing alternative mechanisms, and exploring structural configurations.

The following **sketches** represent early attempts to redefine proportions, internal layouts, and mechanical logic. They do not present final solutions, but rather a process of questioning, testing, and gradually refining the direction of the machine.

Different internal configurations were studied in order to balance compactness, structural lightness, and mechanical efficiency.

Several ideas proved only partially correct, yet they were fundamental in clarifying constraints and possibilities. The sketches reveal a continuous effort to simplify the system while preserving its core principle: constant-force spring resistance integrated into a vertical tower structure.

At this stage, the focus was on **mechanical feasibility and spatial logic** — understanding how components could coexist within a slender and lightweight structure.

The first **3D models** translated the conceptual sketches into spatially measurable systems. These intermediate digital models allowed for more precise evaluation of mechanical relationships and structural coherence.

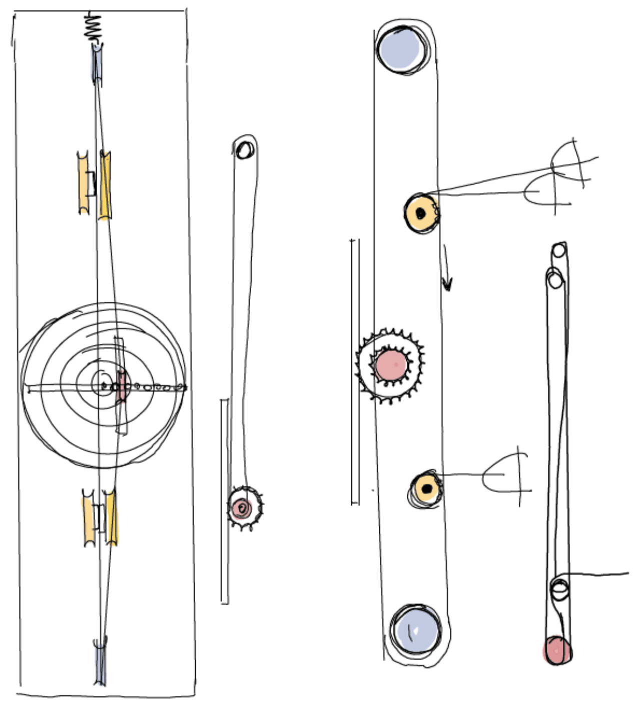


fig. 30 Early sketches studying possible movement solutions

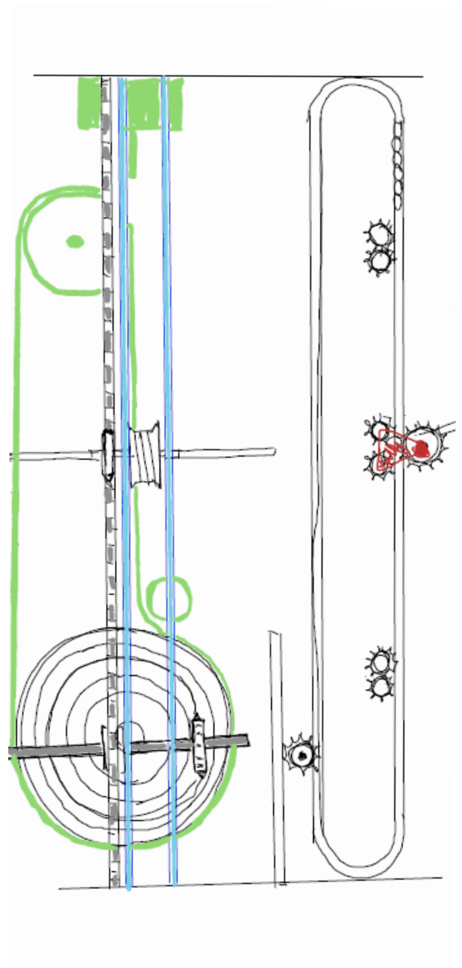


fig. 31 Early sketches of the 2 planes solution

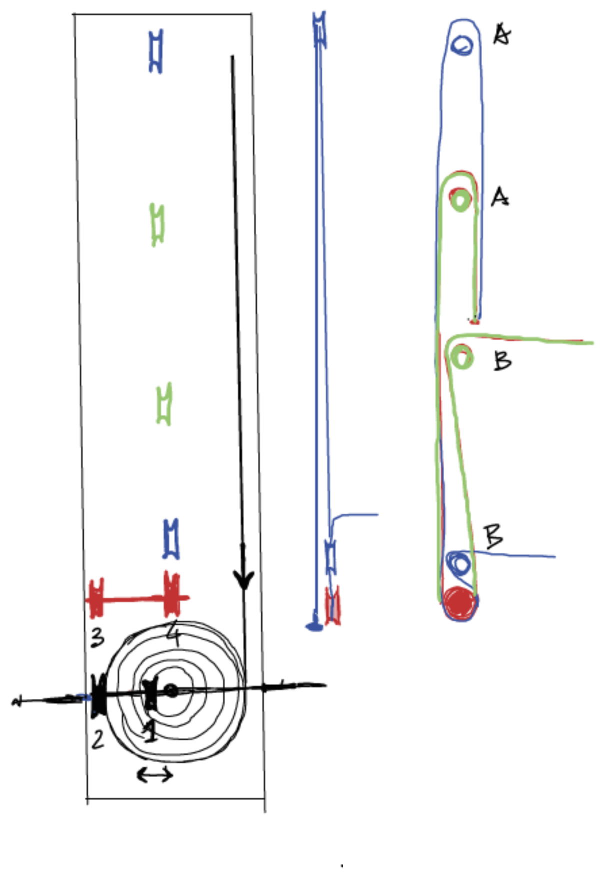


fig. 32 Early sketches of the rising assembly

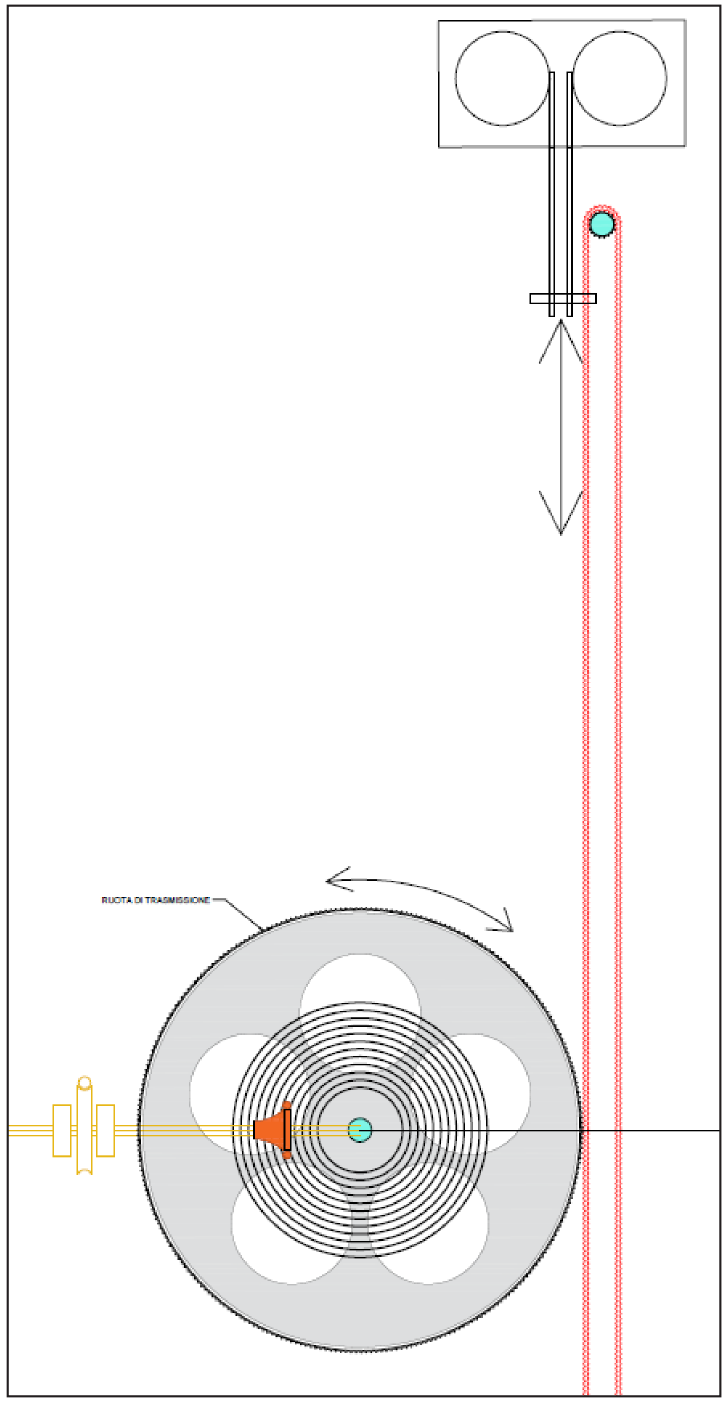


fig. 33 First thought of integrating gears

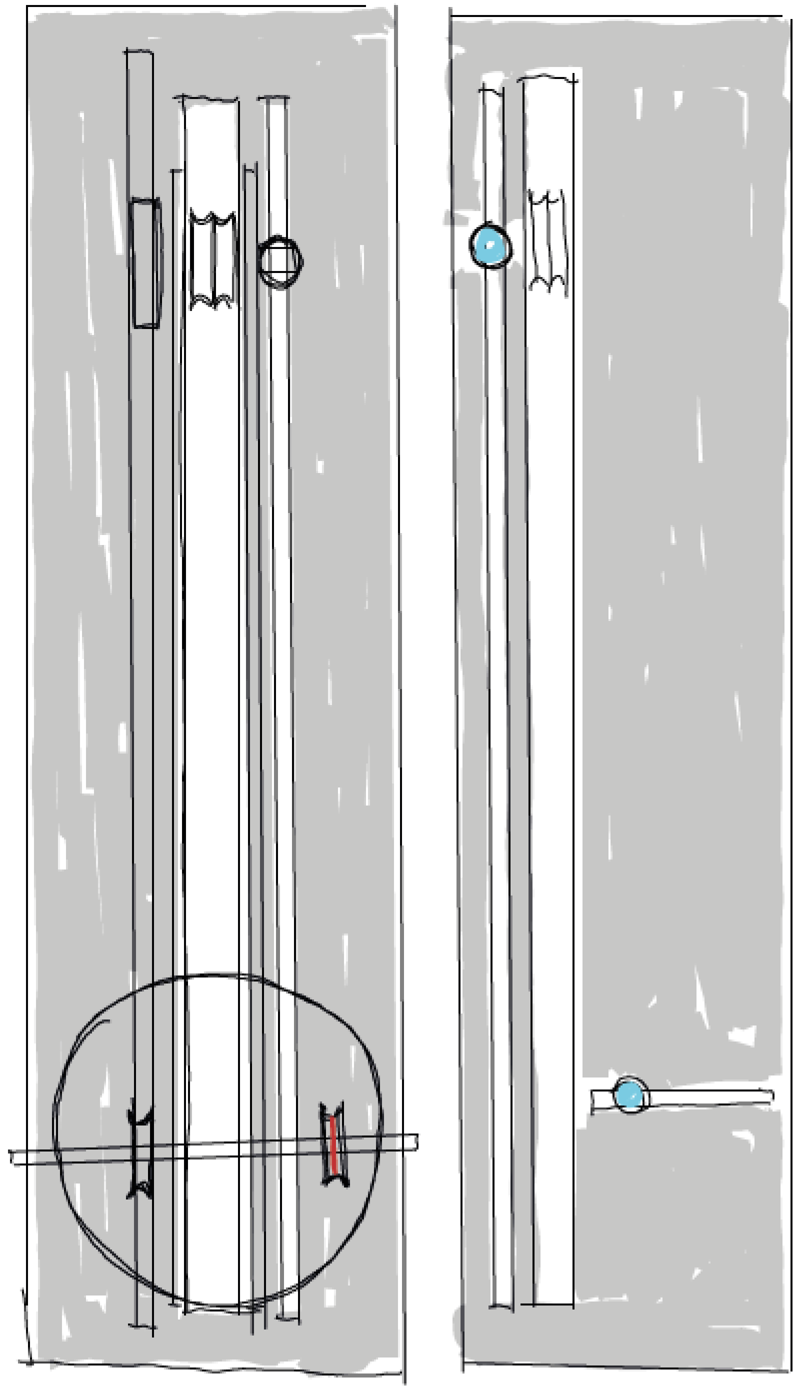


fig. 34 Overall look and dimensioning

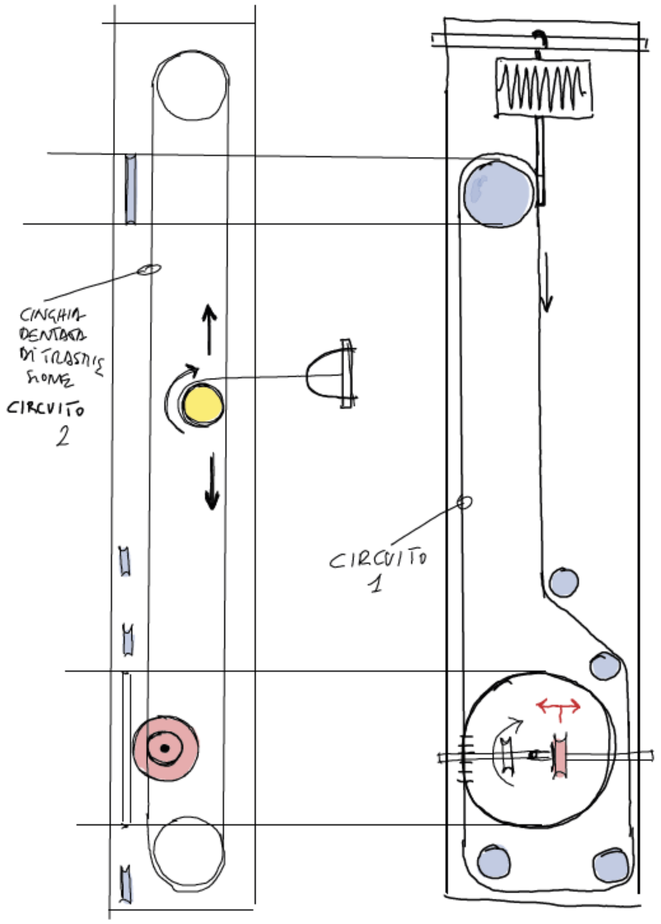


fig. 35 differentiating the 2 planes

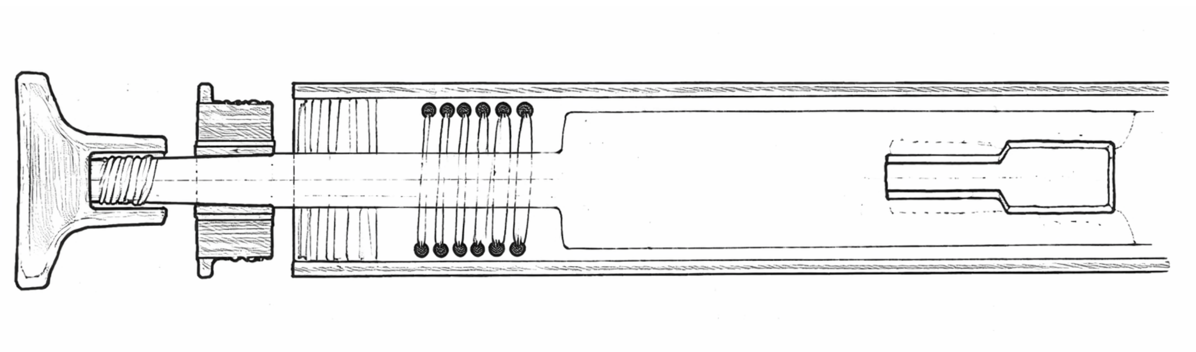


fig. 36 imagining dimensnions and mechanisms

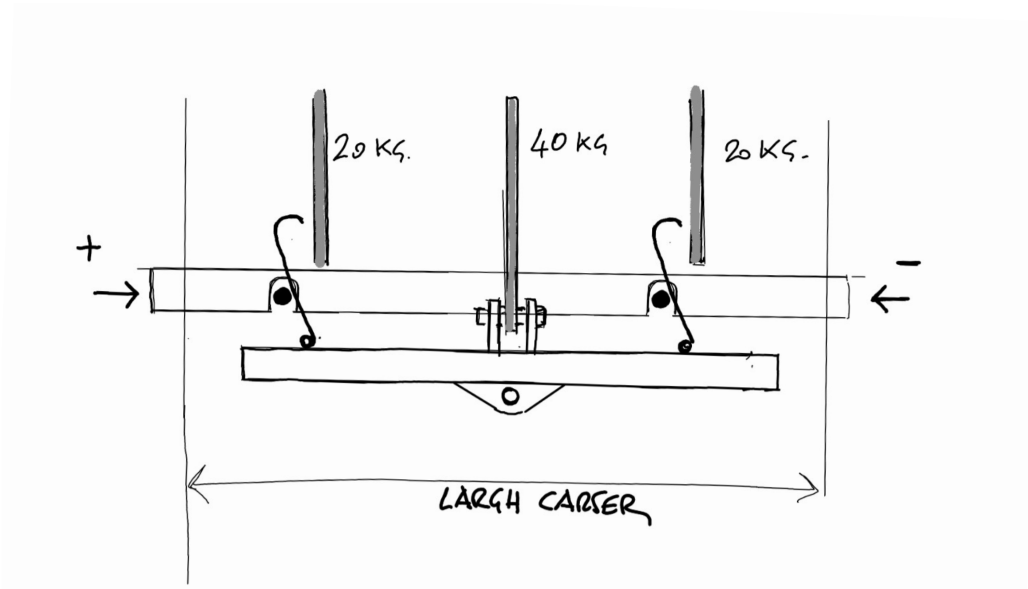


fig. 37 the engagement board

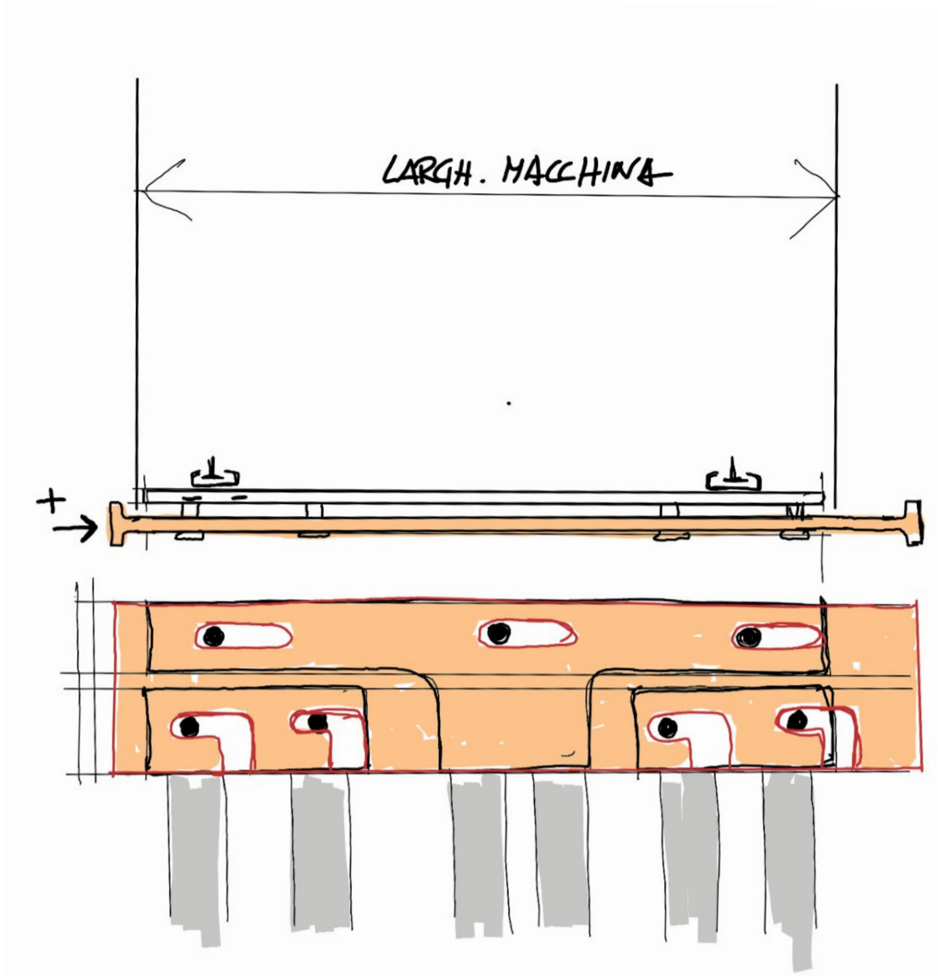


fig. 37 the engagement board version 2

4.2 DESIGN PROCESS (sketches; CAD development)

In the early configuration, two chains were used to manage **two rotational planes** within the transmission system. Over time, it became clear that maintaining both chains was unnecessary and counterproductive. Since the goal was to create a lightweight machine, one of the **chains** was removed and **replaced with a rope**. This solution reduced weight and mechanical complexity without compromising performance.

The crown-and-tooth sliding mechanism was initially modeled in a relatively approximate way. However, the conceptual logic behind it was already valid. For this reason, although it was later refined geometrically and mechanically, its fundamental principle remained largely unchanged.

A significant limitation of the early model concerned the spring pack configuration. All springs were permanently engaged, and the system did not allow for load differentiation or modular engagement. This prevented selective resistance adjustment and reduced versatility. In subsequent iterations, this aspect was redesigned to **allow controlled distribution and modulation of spring loads.**

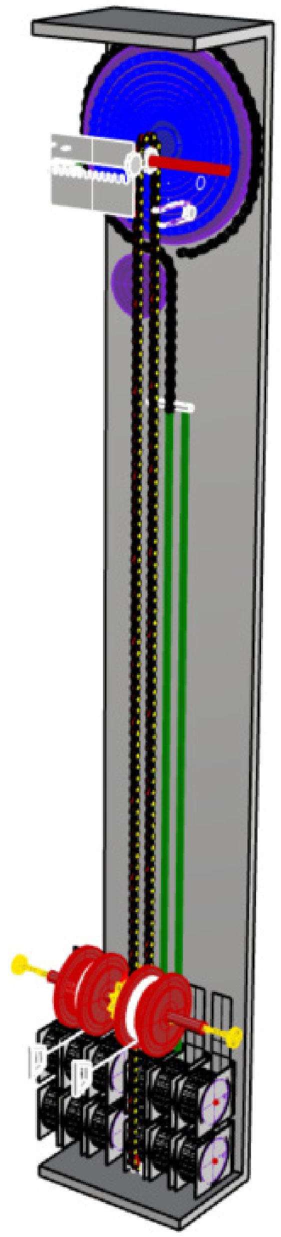


fig. 38 first 3d model

Structural Reorientation and System Optimization

One of the most important conceptual breakthroughs came from fully embracing the intrinsic **property** of constant-force springs: they are **independent of gravity.**

Recognizing this allowed a radical rethinking of the internal layout. The **entire system was rotated 180 degrees** — what was previously positioned at the bottom was moved to the top, and vice versa.

The weight modulation system was repositioned at approximately face height, making resistance adjustment more intuitive and ergonomically accessible.
The heavier structural elements and **spring pack** were relocated toward the **lower section** of the machine, improving overall **stability** and balance.
This reconfiguration significantly improved both usability and structural logic, marking a decisive step toward the refined mechanical concept.

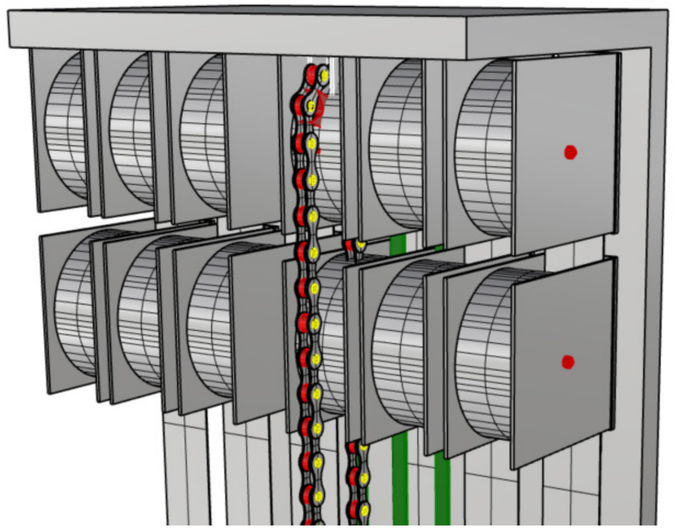


fig. 39 the spring pack

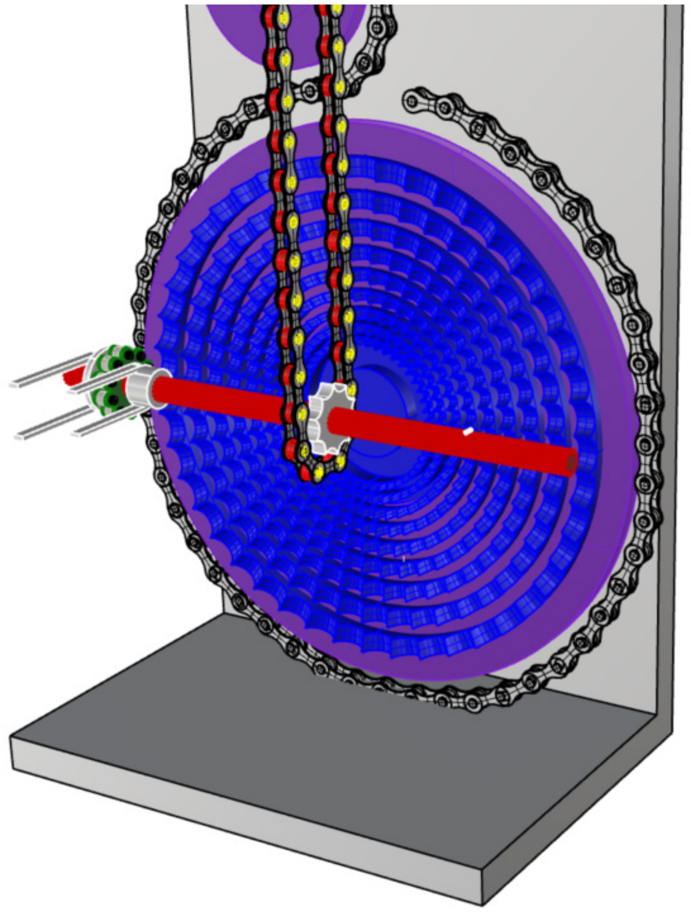


fig. 40 the flat gear system

5. FINAL MACHINE ARCHITECTURE

In this phase, the machine is examined at a level of detail that is sufficiently complete with regard to its internal mechanisms, though not yet fully finalized in terms of its external casing. We proceed with a component-by-component analysis to better understand its operation and the interaction between the various parts.

5.1 THE BASE AND SPRING PACK

The structural core of the machine:

This metal sheet structure functions as the **primary supporting element** for all internal mechanical components. It defines alignment, load distribution, and overall rigidity of the system.
Tandem Spring Configuration
Starting from the base, the constant-force springs are arranged using what Kern-Liebers refers to as a tandem system. This configuration allows multiple springs to be **stacked vertically**, one above the other, in a compact and controlled manner.
In this arrangement, the lower spring extends slightly further vertically at its outer end compared to the upper spring. This deliberate offset allows the two spring ends to be mechanically **joined through** a shared connection **hole**. The geometry and anchoring details were carefully modeled according to the exact dimensions and technical specifications defined in collaboration with the manufacturer.
All **springs were dimensioned, modeled**, and integrated respecting internal **attachment constraints**, usable length, and fatigue requirements agreed upon during the engineering phase.

Spring Pack:

Division into Three Spring Packs
The springs are divided into three functional groups:

1 **Central Pack**
- Composed of four springs
- Always engaged
- Each spring provides approximately **4 kg of resistance**
- Total base resistance: **16 kg**
- Minimum life cycle**: 30,000 cycles**

These central springs form the mandatory baseline resistance of the machine.

2 Right and Left Packs (Optional Packs)
- Eight additional springs in total
- **Engaged only when selected by the user**
- Must be engaged together
- Allow resistance progression from **16 kg up to 80 kg**
- Each spring also rated for 30,000 minimum life cycles

From a practical standpoint, assuming a user trains three times per week for approximately 90 min per session, these springs are estimated to last roughly **two and a half years** at least.

fig. 41 the base and springs of the machine

5.2 THE SHIFTING ENGAGING PLATE

Directly above the spring assembly sits an engagement plate. This plate features **protruding engagement pistons** that mechanically **connect** or **disconnect** the right and left **spring packs.**
A **secondary horizontal sliding plate**, positioned at the front right side of the structure, controls this mechanism. By moving this plate laterally (left–right), the user can engage or disengage the additional spring packs.

- When the system **displays "Low",** only the central pack, 16 kg is active.
- When the system displays "**High"**, all spring packs are engaged, allowing resistance up to **80 kg.**

This movement is manual, intuitive, and directly linked to the internal mechanical engagement.

Visual Feedback and Structural Guidance
The engagement bar position directly corresponds to visible resistance indicators on the shell.
Additionally, the back plate includes two carriage guides that eliminate lateral play. These guides stabilize **the engagement plates** and ensure controlled movement along the supporting rear wall. This prevents unwanted oscillation, improves durability, and guarantees precise mechanical alignment.

Design Intent
This base configuration achieves several objectives:

- Compact vertical integration of high-force springs
- Modular resistance configuration
- Clear separation between structural core/ aesthetic shell
- **User-friendly** and mechanically safe load engagement
- Long operational lifespan

The structural base is therefore not just a support element, but the mechanical heart of the machine where force generation, modulation, and stability are engineered into a cohesive system.

fig. 42 engagement plate

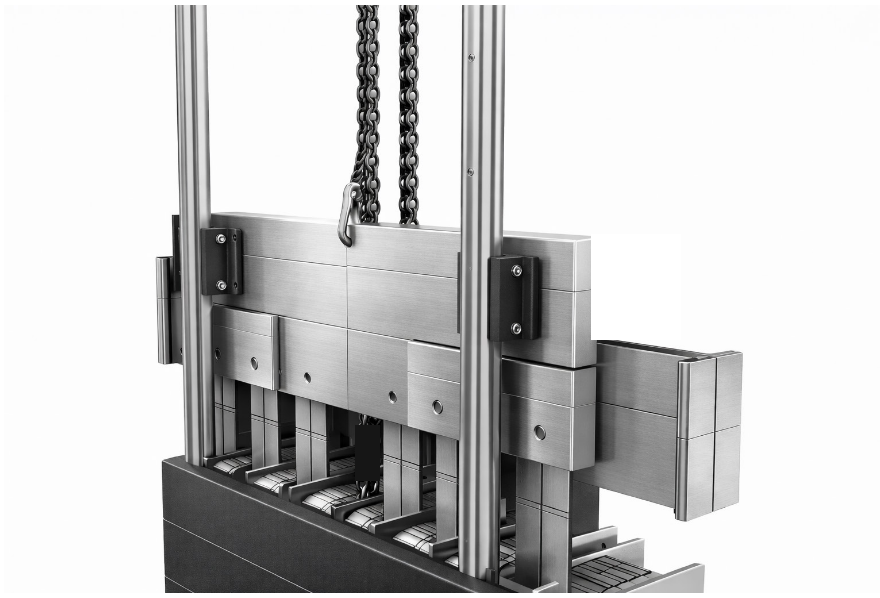


fig. 43 engagement plate and sliding plate from behind with rails

5.3 CONNECTING ROPE

This **rope** serves as the primary transmission element between the plate (spring packs) and the upper mechanical system, **lifting the engagement pate upwords.**

The rope is fixed at the center of the engagement plate and travels vertically along the central axis of the machine. Its motion is guided by the two rear **linear rails,** ensuring stable and precise vertical displacement of the entire spring system.
The decision to use a rope instead of a chain or rigid linkage was because performance ropes are capable of sustaining loads of several hundred kilograms, far exceeding the requirements of this machine. At the same time, they offer significant advantages in terms of **reduced friction**, lower **noise** generation, and overall **lightness**. Since one of the project's main objectives was to create a lightweight and mechanically efficient machine, the rope represented the most rational solution.

As the rope rises, it passes over a **directional pulley**. This pulley's sole purpose is to maintain vertical alignment and ensure the correct wrapping angle around the sprocket plate.
After the pulley, the rope is secured using a set screw inside the outermost diameter of the sprocket plate. **The sprocket plate** features **a seating groove** that allows the rope to rest and wrap correctly without lateral displacement.
The total rope length is so that it can wrap around the sprocket plate no more than once.
This ensures two critical conditions:

1. The **springs can extend fully,** reaching their maximum usable travel of approximately **1.3 meters.**
2. The rope does **not** accumulate multiple **overlapping turns** around the sprocket plate, preserving consistent transmission.

This controlled wrapping system ensures efficient force transfer, full spring utilization, minimal friction losses, and quiet operation throughout the entire range of motion.

fig. 44 The rope - onnection with the upper part of the machine

5.4 THE GEARBOX AND SHIFTING MECHANISM

This component explains **how** the **sprocket plate rotates** and winds the rope that pulls the spring assembly from below.
The rotation of the sprocket plate is mechanically linked to **a crown positioned on a perpendicular plane.**
This crown has a diameter of 80 mm and features **11 "teeth**," which are not traditional gear teeth, but circular bearings, each with a diameter of 8 mm. The **pitch** between these teeth is 11.27 mm. This same pitch is replicated across the geometry of the sprocket plate to ensure correct meshing and functional coherence between the two components.
The tooth geometry of both the crown and the sprocket plate was carefully designed to guarantee that **at least two bearings** are always **engaged** at any given time. This ensures continuous contact, smooth torque transmission, and mechanical stability. At the same time, the geometry prevents excessive contact points that could create friction peaks or locking conditions between the crown and the sprocket plate.

The sprocket plate itself consists of multiple **concentric circular tracks**, each with a different number of teeth (for example 109, 102, 96... always jumping 6/7 teeth to maintain a constant variability), while maintaining the same pitch. What changes from one circumference to another is not the spacing between teeth, but the total number of teeth which determines the effective transmission ratio (16 total).

Rest Position and Gear Selection Logic:

When the springs are fully relaxed, the sprocket plate presents a specific **alignment condition: the "valleys"** between the teeth along one defined radial line are perfectly aligned across all concentric tracks. This alignment occurs more than once in the sprocket plate but to us its only important to align one consinstent path where the **crown moves horizontally** (when the system in not under tension).

In this rest condition, the crown bearing can move freely left or right, assisted by the user. This allows the user to select which concentric track (or "gear") to engage.
Once a **specific track is selected, the crown engages** that circumference, producing a defined transmission ratio and consequently a **specific load demultiplication**. In this way, the system functions similarly to a gear shift: by choosing a different track, the user modifies the mechanical advantage and therefore the perceived resistance.

This configuration enables:

- Controlled and smooth engagement
- Reduced friction and no locking points
- Reliable torque transmission
- Clear mechanical differentiation between load settings

The sprocket plate and crown system therefore represent the core of the load modulation mechanism, t**ransforming vertical rope displacement** into **controlled rotational transmission** and adjustable mechanical advantage.

fig. 45 he moving crown along its path

The crown:

is composed of multiple assembled components rather than a single solid piece.
Each circular “tooth” consists of a bearing element laterally contained by two 2 mm side plates, which ensure axial stability.
Outside these are two thrust ball bearings that allow the rotation of the bearing cover plates relative to the outer structure along, enabling smooth engagement without excessive friction.
The entire assembly is **held together by a bent metal plate** and supported by a keyed hollow central tube that provides more slide with (female key) transmission shaft, ensuring secure torque transfer.
The extended metal structure also acts as a **manual lever**, allowing the user to shift the crown laterally, engage a new notch, and **change** the **transmission ratio** — effectively selecting a different resistance level.

The transmission shaft:

is connected horizontally to a toothed **gear** whose sole function is to transfer rotational motion directly to the vertical chain. This gear acts as a simple and efficient link between the rotational system (generated by the sprocket plate and crown mechanism) and the final mobile component of the machine.
At the center of the machine, aligned vertically, there is a **closed-loop chain.** This chain forms a continuous ring positioned along the central axis of the structure. It represents the final transmission stage, connecting the internal mechanical system to the movable training element.
Through this arrangement, rotational motion is efficiently converted into controlled vertical displacement, **completing the mechanical path** from the spring system **to the user** interface.

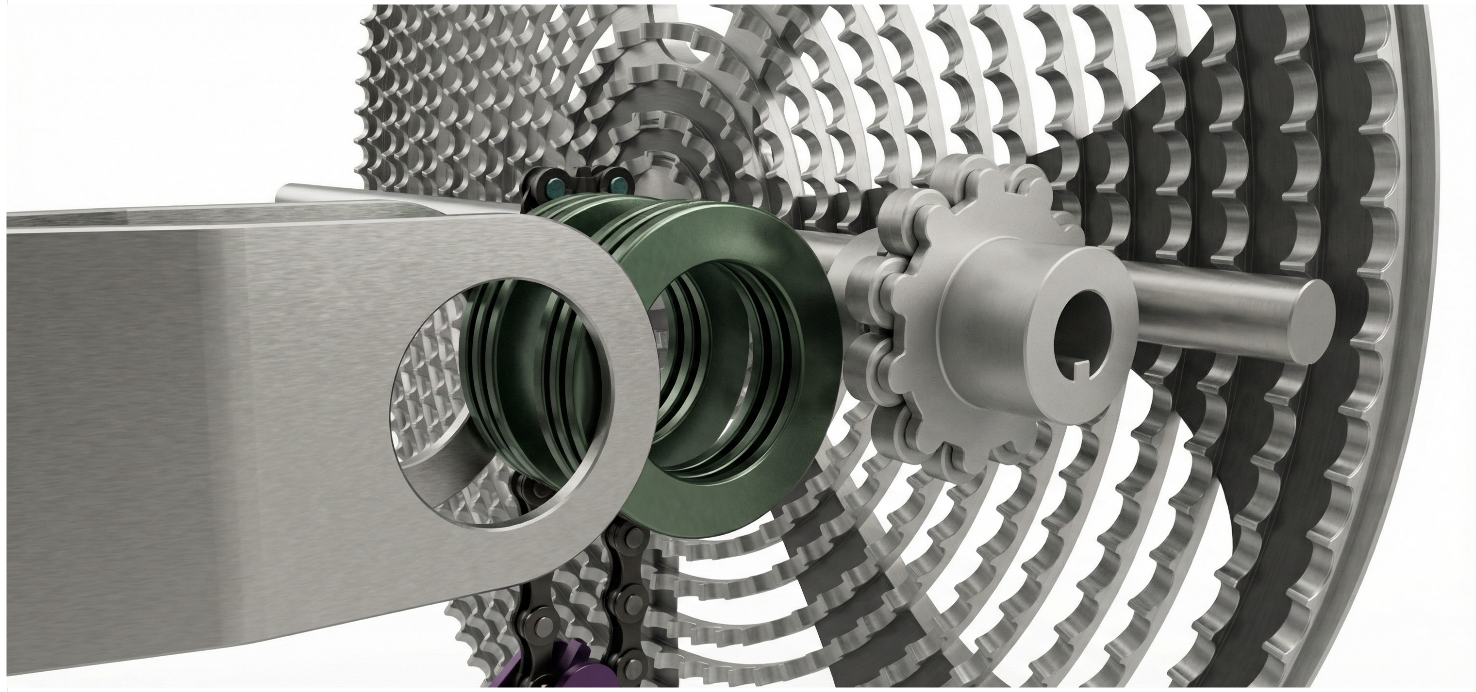


fig. 46 Assembly of the crown pack

5.5 DRUMS & VERTICAL ADJUSTMENT

Engaged to the vertical chain is the **entire pulling system**: the final mechanical interface between the internal transmission and the user.
This assembly is supported by two lateral metal walls forming the vertical structure of the machine. Along these walls, adjustment holes are positioned at 10 cm intervals. These notches allow the entire pulling system to be locked at **different heights** across the full vertical range of the machine, enabling exercise customization based on user height and movement requirements.

Central Shaft and Chain Engagement
At the core of this system is a horizontal tube that spans from one side of the machine to the other. At the center of this tube sits a gear that meshes precisely with the vertical chain. Both the gear and the chain share a 20 mm pitch, **ensuring** accurate and reliable **engagement**.
The **central gear** is supported by two lateral plates that host 2 small opposing guide gears. These stabilizing gears press against the opposite side of the chain, ensuring constant alignment and preventing disengagement or misalignment during operation. This guarantees smooth and secure torque transmission.
The main gear is **rigidly** connected to the h**orizontal tube**. When the tube rotates, it drives the chain, **completing the force transmission path**.

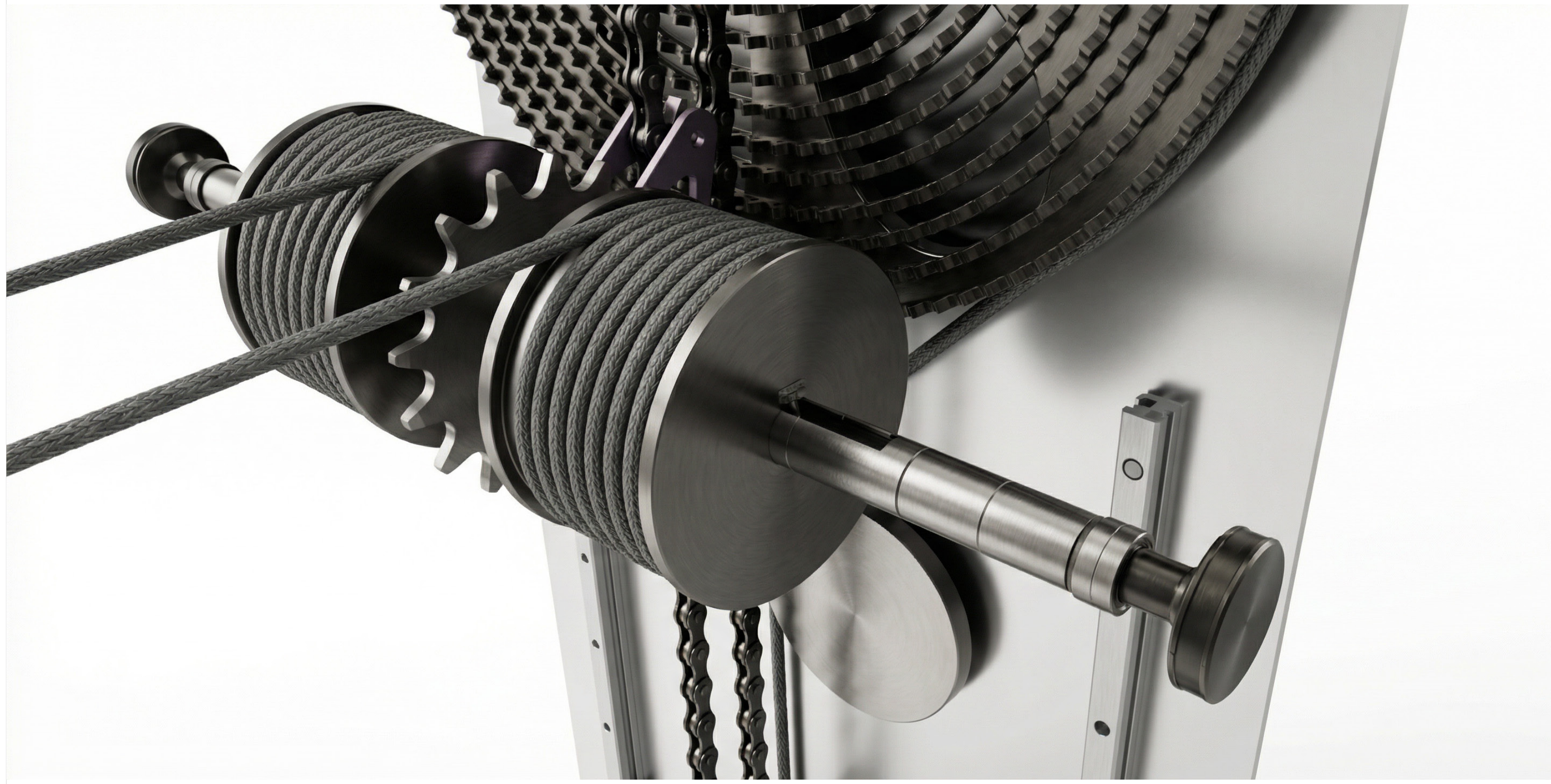


fig. 47 The drums and vertical adjustment system

Mounted on the horizontal tube are one or **two drums.** These drums unwind when the user pulls the cable and rewinf naturally because of the spring's tension. The cable itself consists of a 6 mm internal metal core with a plastic outer coating, wound around the drums. It provides a maximum travel of approximately **two meters** (**7 total laps** around the drum) more than sufficient for all intended exercises.

The **drums** have the **same diameter** as the **central gear (100mm).** This dimensional consistency prevents any unintended force de/multiplication in this section of the mechanism.
Each **drum is keyed (locked)** to the rotation of the central tube, However, this key can be **disengaged**. When disengaged, the drums rotate freely, allowing independent repositioning of the **moving system.**

Engagement and Vertical Adjustment Mechanism
The keys that lock the drums to the tube can be disengaged by **pulling outward on two protruding elements** located at the ends of the tube. These components are spring-loaded inward, keeping the drums engaged during operation. With a small applied force, the user can overcome the spring tension, **disengage the keys**, and allow the drums to rotate freely.
This feature makes vertical repositioning simple and efficient.
Once disengaged, the central gear can rotate freely along the chain without transmitting torque, allowing the entire system to move smoothly to a **new height.**

fig. 48 Render section of the height adjustment mechanism

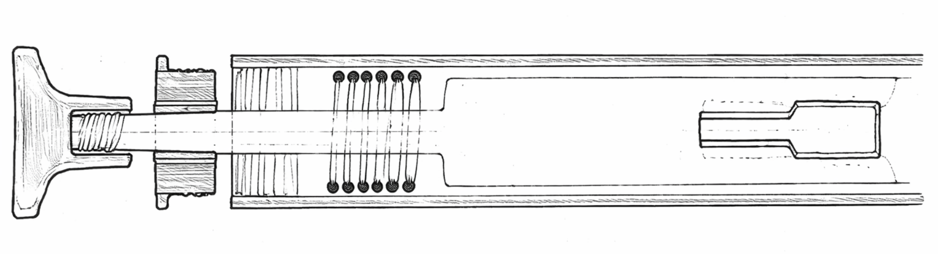


fig. 49 Sketched section of the height adjustment mechanism

fig. 50 The main complex rod of the system

The lateral locking systems function similarly to standard vertical adjustment levers or knobs found in gym equipment. However, in this case, they were adapted to perform a **dual function**: **both vertical locking and rotational engagement/disengagement of the drums**.
The drums are engaged only when the machine is ready for resistance and the user is prepared to perform the exercise. This ensures mechanical **safety**, intuitive operation, and seamless transition between adjustments and active training phases.

Dual Drum Spacing and Handle Prototype
The two drums are positioned at a **predefined distance** from each other. This spacing is relatively close, yet carefully optimized to allow the execution of nearly all pull exercises where both hands operate close together.

To enable both wide and narrow grip variations using the same system, I developed an initial prototype of a connecting attachment. By **linking the cables** from the two drums into a single interface, this component allows the user to perform:

- **Wide** pulling movements, such as a broad rowing motion
- **Narrow** pulling **exercises**, such as a tricep pushdown

This attachment acts as a modular connector, transforming two independent cable outputs into a unified or **adjustable grip system**. It expands exercise versatility while preserving the compact architecture of the machine.

fig. 51 The equipment and possible handles/grip

5.6 USER INTERACTION AND MECHANICAL INTERFACE

The user interface was designed with clarity, simplicity, and safety as primary objectives.
For **resistance selection**, the **High/Low engagement bar** is designed so that only one label is visible at a time. The bar extends beyond the total height of the machine and protrudes either to the right or to the left, clearly indicating the selected configuration. With a simple inward push of the hand, the user can engage or **disengage the additional spring packs**. The movement is direct, intuitive, and immediately visible.

For **transmission ratio adjustment** (load demultiplication), the system is equally straightforward. The **user slides the regulator** laterally, shifting the crown onto a different track of the sprocket plate. Each track corresponds to a clearly marked resistance level displayed below. By selecting a different seating position, the user effectively changes the mechanical advantage.
This approach improves not only usability but also **safety**. The entire mechanism is enclosed within the structure, preventing access to internal moving parts. There is **no need to insert hands i**nto the machine or interact with exposed components under tension. As a result, load adjustment becomes both intuitive and mechanically secure, providing a frictionless and protected user experience.

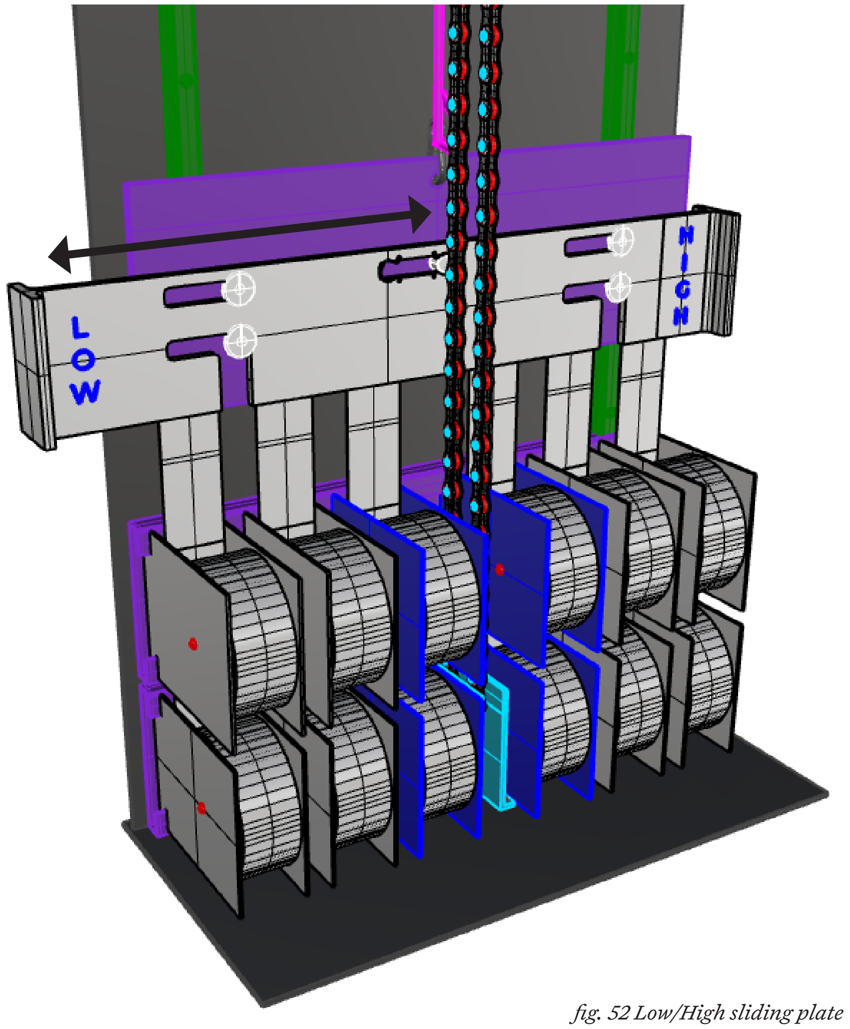


fig. 52 Low/High sliding plate

6. CONCLUSION

This thesis challenged the assumption that weight must be the primary source of resistance in strength training equipment. By **redefining resistance** as a controllable mechanical force rather than a gravity-based load, the project explored how constant-force springs could reshape the structural logic of gym machines.

The final machine demonstrates that constant-force springs can provide scalable, compact, and **gravity-independent resistance**, while integrating complex transmission systems into an intuitive and user-friendly structure.

However, this work represents a foundation rather than a finalized commercial product. Future developments could include fatigue optimization to extend life, further material research to reduce structural weight. Additional **biomechanical testing** would be essential to quantitatively validate the resistance profile in comparison with traditional weight-based systems and see if it really has potential in the rehabilitation contexts. Constant and low-inertia resistance could support controlled therapeutic protocols. **Further development** may include modular accessory components to expand exercise variety, as well as a clear definition of installation strategy whether wall-mounted, or integrated with a dedicated base platform to ensure structural stability and safe real-world application.

Ultimately, this thesis demonstrates how design engineering can operate as a bridge between **mechanical depth** and **human interaction**. By making resistance invisible, compact, and intelligently transmitted, the project challenges the symbolic dominance of iron in strength culture and proposes a new paradigm: strength training driven not by mass, but by engineered force.

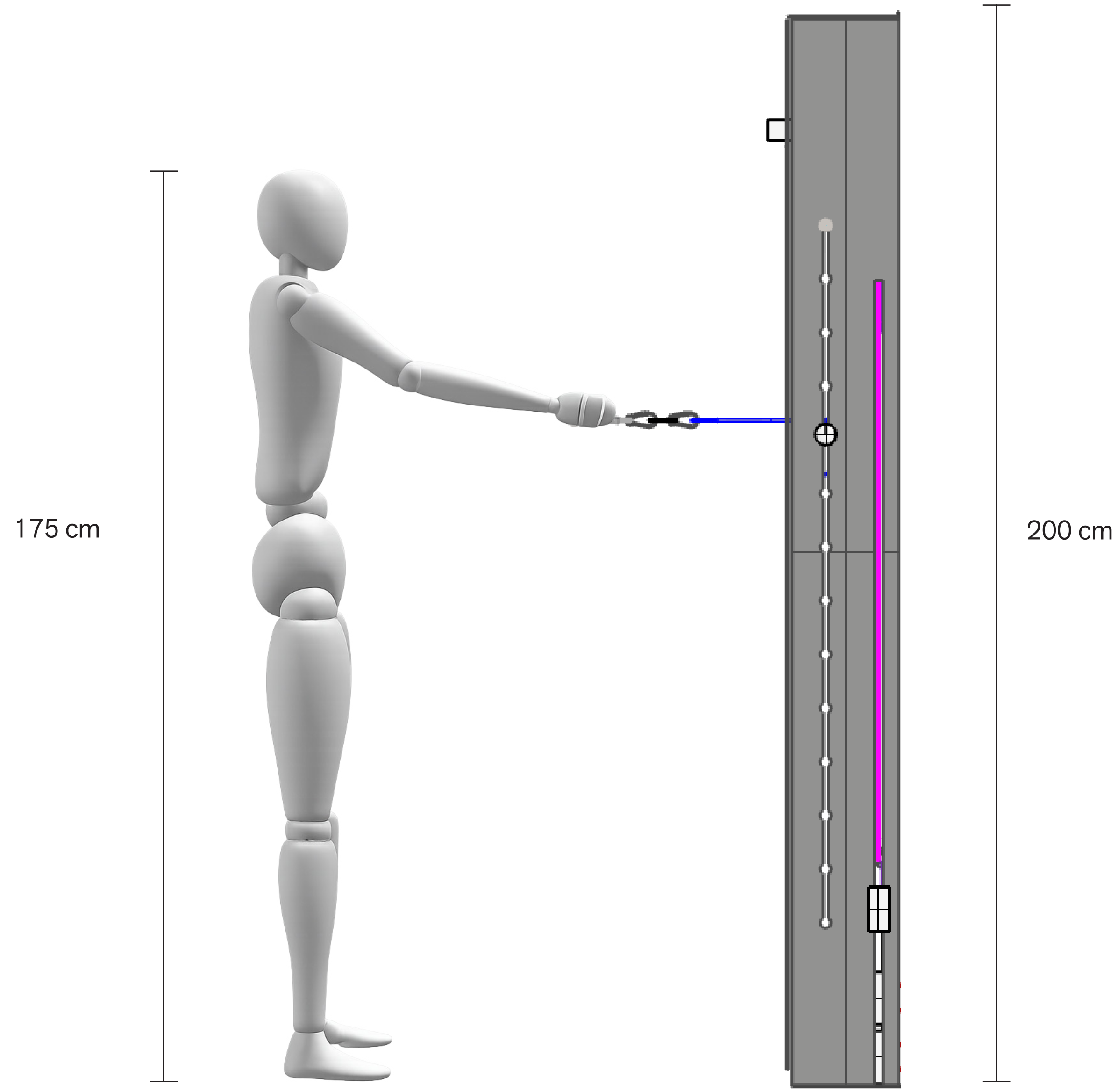


fig. 53 Actual dimensions

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8. LIST OF FIGURES

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thanks POLIMI