TECHNISCHE UNIVERSITÄT WIEN

Diploma Thesis

Concept development of a modular product variant for electronic strength training machines through evaluation of biostatistical data

carried out for the purpose of obtaining the degree of
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Affidavit

I declare in lieu of oath, that I wrote this thesis and performed the associated research myself, using only literature cited in this volume.

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Abstract

The aim of this Master's thesis was to develop a concept for a new product series that can co-exist with the current product series rather than cannibalize it. Furthermore, a modular product strategy should be satisfied to generate synergy effects in terms of material and production costs.

The biostatistical data obtained from the software company milon Care is analysed to determine which changes need to be addressed for the current product series with respect to proper loading and adjustments for the user's physiological training position (e.g. range of motion, seating height). The concept for the new product series is developed under the premise to satisfy at least the 95th percentile of all users.

A function cost matrix was developed to display the component groups with the greatest cost reducing potential. The ideas and concepts for alternatives were evaluated through a feasibility study with the head of the mechanical R&D department and a cost reducing potential estimate with the head of the purchasing department.

Finally, the implemented concepts were visualized for the machines Chest Press and Back Extension. It is estimated that for the batch 1 strength machine circuit a cost saving potential of 12.93% is achieved through the concepts for alternative components, structures and materials.

Contents

List of Figures

List of Tables

Acronyms

ABS Acrylonitrile butadiene styrene
ACh Acetylcholine
ACSA anatomical cross-sectional area
ADP Adenosindiphosphate
ATP Adenosintriphosphate
ATPase Adenylpyrophosphatase
B2B business to business
COM center of mass
CTS connected training system
DSSV Deutscher Sportstudio Verband
G maximum load of the machine
G_K force determined by the proportional body mass
GUI Graphical User Interface
IKM initial isokinetic measurement
JSON JavaScript Object Notation
MC milon coin
Mdn Median
MPG Medizinproduktegesetz
P Phosphate
PCSA physiological cross-sectional area
PMMA Poly(methyl methacrylate)
PS Polystyrene
R&D Research and Development
RM repetition maximum
ROM range of motion
USP unique selling proposition

1. Introduction

Many countries in the world are experiencing an absolute as well as a relative increase in older adults in proportion to the rest of the population. With this continuing trend it is projected that by the year 2050 a total of 82 countries will have at least 20% of their population being 65 years and older in comparison with 13 countries as of 2018 [41]. This demographic change and a growing health awareness of the population results in an increasing number of people especially the elderly to exercise preferably in training studios. Europe Active and Deloitte annually releases "The European Health and Fitness Report" summarizing market development, data and trends in the European fitness market. The current report shows that there was an increase of fitness clubs by 4.6% across all countries in the European Union, leading to an increase in membership of about 3.5% [44, p. 9].

Progressive strength training increases muscle volume and is especially important for the elderly to stay mobile for their everyday activities [35]. Furthermore, strength training in medical rehabilitation centres incorporated to strengthen muscle, stabilize structures and prevent from further injuries will be more and more of importance with the ongoing ageing of society. For inexperienced, untrained and previously injured people the training on strength machines is favoured as the movement path is guided. Movement corrections can more easily be done by the trainer compared to exercises using free weights. However, experienced coaching is necessary to prevent the users of strength training machines of injuring themselves by performing movements in a wrong manner.

Technology can play a crucial role in assisting the trainer or therapist for an optimal care of their customers. Nowadays it is possible to collect a vast amount of data especially through smartphone apps and wearables (e.g. fitness trackers, smart watches). The collected data includes for instance amount of steps, heart frequency or even pulse oximetry to determine the oxygen saturation in the bloodstream. Analyses can be made upon sleep quality, activity, stress level and many more.

Not surprisingly manufacturers of fitness products explore the new movement of a quantified self. Nowadays it is possible for certain strength training machines to gather biostatistical data from the interaction with the user. The analysis can help the trainer or therapist for instance to adjust proper loading to prevent (further) injuries or incrementally increase loading for muscle adaptation leading to strength progression. The usage of this quantifiable data is a more efficient way to satisfy the customer's needs and increase their training efficacy. Furthermore, it is possible for the owner of a training studio or medical rehabilitation center to properly manage more customers. The created data sets are also of great importance for the training machine manufacturer. In a way the company gets to know its customers through the gathered data without directly contacting them. Due to current technology it is not an issue anymore to gather and store large amount of data. Nevertheless, an interpretation has still to be made for the data regarding its value. There is a great opportunity to evaluate existing machines on their effectiveness and predict what the user needs.

1.1. Statement of Problem

The first issue arising from the amount of data variables is how to apply them for an evaluation of existing strength training machines. In addition, an expansion of the product portfolio is desired by the company. Furthermore, there is the issue how to develop a cost reduced product variant without generating extensive developing efforts and integrate it into the existing production processes preventing an increase in production time and cost with respect to the machines of the current product series. The challenge is to offer an optimal product portfolio for the customer, but at the same time ensure the highest possible internal standardization.
In conclusion following issues should be investigated by this Master's thesis:

- What data variables need to be queried and what conclusions can be drawn with respect to different strength training machines?
- How can a product variant be integrated in the existing product portfolio without generating high development and production costs?

1.2. Aim

Through the evaluation of biostatistical data the proper development of training machines should be reviewed. Thus, it should be investigated what benefits the data can bring for the company in satisfying customer needs.
A method for a systematic expansion of the product range should be developed to reduce material and production costs in the long term. The aim is a concept for a new product series that can co-exist with the current product series.

2. Theoretical Principles

2.1. Function of skeletal muscle

In the humans' locomotor system the skeletal muscles can be considered as actuators driving skeletal movement. Other functions include assisting in joint stability, and maintaining posture and body positioning [20, p. 62]. A skeletal muscle normally connects two bones. The connecting side closer to the trunk (proximal) is called muscle origin, further away (distal) muscle insertion. Skeletal muscles have the task to move origin and insertion closer together upon contraction [34, p. 116].

2.1.1. Hierarchical muscle structure

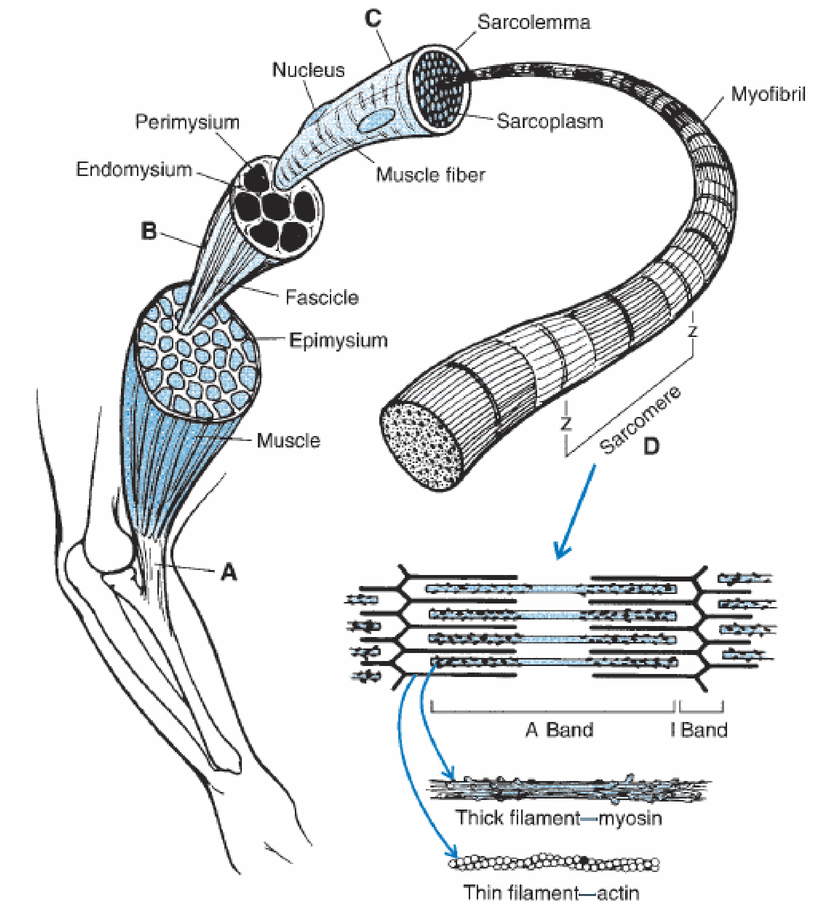
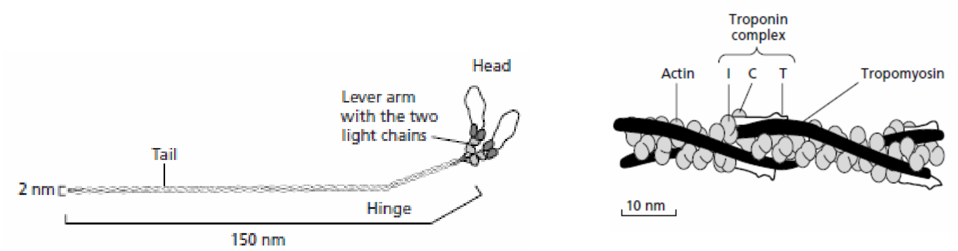


Figure 2.1: (**A**) Muscle connected to bone through tendon. (**B**) Fibre bundles within fascicle. (**C**) Bundle of myofibril strands. (**D**) Sarcomeres, the contractile unit, connected in series [20, p. 66]

Like with many systems in the human body the muscle is organized through a structure of hierarchy (see figure 2.1). A muscle consists of a large amount of fascicle bundles, which itself consists of a large amount of muscle fibres. Those muscle fibres can be broken down into myofibrils containing the contractile proteins of the muscle, the sarcomers [20, pp. 65-66]. These contractile units consists of longitudinal thick (myosin filament) and thin (actin filament) elements (see figure 2.2) arranged between Z-discs, which are spaced about 2.5μm apart [27, p. 50].



(a) Myosin molecule with two intertwined heavy chains in each head and two light chains to stabilize the lever arm at base of head

(b) Thin filament with two intertwined strings of actin with adjoining tropomyosin bound to it inheriting a troponin complex.

Figure 2.2: Myosin (a) and actin (b) molecule [27, p. 52]

The myosin heads, which cause a shortening of the sarcomere by bending, are the force-generating sites in muscle using. The energy for contraction is derived from the hydrolysis of Adenosintriphosphate (ATP) to Adenosindiphosphate (ADP) and Phosphate (P) [27, pp. 50-53].

2.1.2. Muscle contraction

In terms of functional organization the muscle can be split into motor units, i.e. the innervation of several muscle fibres by the same motor neuron. An intentional muscle contraction is achieved through transmitting a signal, the action potential, from the motor neuron to the muscle [20, pp. 66-67]. The connection side of the nervous motor nerve fibre at the muscle fibre is called motor endplate (Terminatio neuromuscularis) [34, p. 116]. The incoming action potential leads to a release of neurotransmitters, in this case Acetylcholine (ACh), by the synapse [8, p. 139]. ACh binds to receptors at the postsynaptic membrane and generates muscle action potentials. The wave of depolarization is propagated through the T-tubule system. That system consists of deep invaginations of the muscle cell's plasma membrane (sarcolemm) and enables a faster transmission of the depolarization wave to the inside of the cell. Sarcoplasmatic reticulums are located right next to the tubuli, which serve as reservoirs for Calcium (Ca^{2+})-Ions. Dihydropyridine receptors are located in the membrane of the t-tubules and change their conformation upon depolarization. Ryanodine receptors, which are located at the end (terminal cisternae) of the sarcoplasmatic reticulums react to the conformation change by opening their channels. Through this receptor coupled process Ca^{2+}-ions are released to initiate the contraction process. Those ions cause a shifting of Tropomyosin through binding to Troponin C, which uncovers the binding site of the actin for the myosin heads [8, p. 140].

Sliding filament theory

Huxley (1957) proposed a model to describe the contraction process in his sliding filament theory. The contraction of a muscle is hereby achieved through the shortening of the individual sarcomeres. The myosin head inheriting ADP and P binds to the adjacent side of the actin filaments by releasing P and thus forming cross-bridges. By releasing ADP a bending of the myosin head results in a sliding of actin into the A band of the sarcomere between the myosin filaments (see figure 2.1). The myosin head then detaches upon ATP binding and moves on to the next actin site. Adenylpyrophosphatase (ATPase) split ATP into ADP and P, which marks the beginning of a new cycle. That cycle is repeated by many myosin heads to bring the actin filament further towards the center [27, p. 53].
Figure 2.3 illustrates that the filaments do not change their length, but the sarcomere does. The shortening of many sarcomeres shortens the myofibrils and fibres developing tension through the muscle. Through connection to the bones at both ends a movement is created.

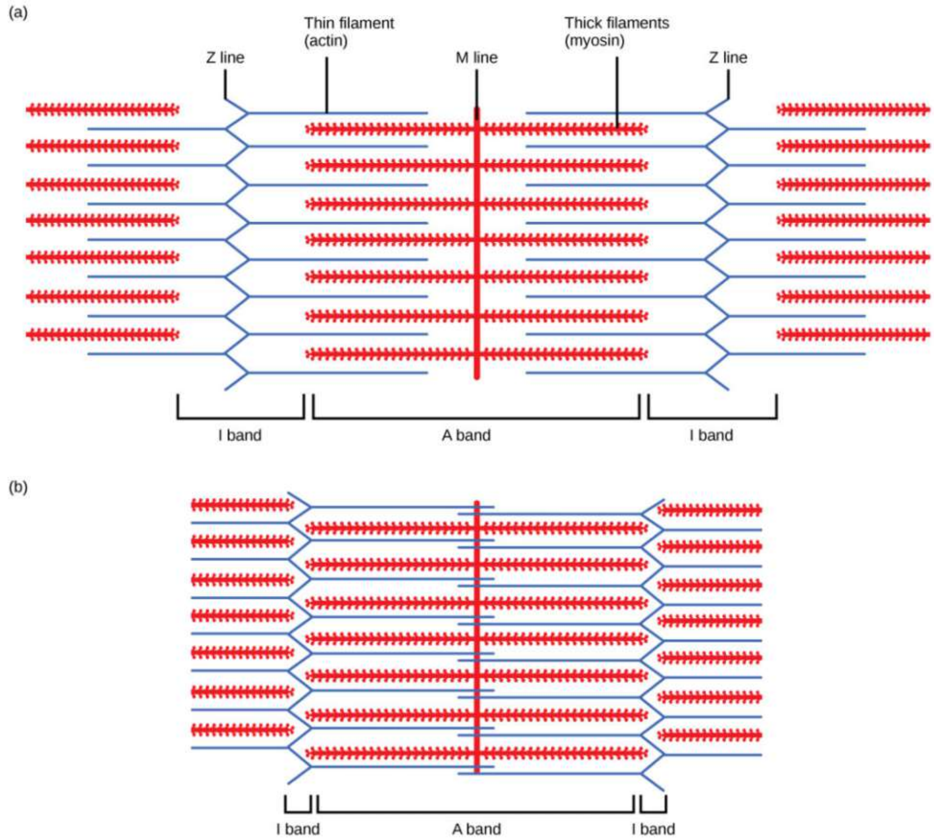


Figure 2.3: Sarcomere in a (a) relaxed and a (b) contracted state[1]

2.1.3. Different muscle fibre types

The basis for occurrence of different muscle fibre types is due to the fact that sarcomeres can have different molecular forms (isoforms). The differences arises from the ATPase rate operating in the myosin heads. Thereby a fast myosin head is estimated to cleave with a rate of 80 ATP/seconds and slow myosin head at a rate of approximately 16-26 ATP/seconds [27, p. 59].
Most of the skeletal muscles contain a combination of different fibre types with different properties. They are categorized into slow-twitch fibres (type I) or fast-twitch fibres (type II) with mechanical response differences [20, p. 65]. Slow-twitch fibres are often called red fibres as they inherit a great amount of the protein myoglobin, which is the red coloured oxygen transport molecule. They are intended for tasks which demand low intensity continuous performance, like walking or standing, with a slow fatigue rate

[1]figure retrieved from URL: https://courses.lumenlearning.com/wm-biology2/chapter/sliding-filament-model-of-contraction/, last visited 18th June 2019

due to the great amount of mitochondria [8, p. 146].
The type II fibres are further divided into intermediate-twitch (type IIa, oxidative-glycolytic) and fast-twitch (type IIb, glycolytic) type fibres. Type IIa fibres do have a high oxidative metabolism with a fast ATP supply. They are intended for endurance activities as well as fast contraction with subsequent fatigue. Type IIb fibres have a small amount of mitochondria and gain ATP through anaerobic glycolysis, which happens under exclusion of oxygen. Consequently they are termed white fibres and fatigue very fast. Their task is a rapid force production [8, p. 146].
Comparing two type of runners and the respective muscle groups they rely on, for instance the m. gastrocnemicus, it can be said that a sprinter has a greater concentration of fast-twitch fibres compared to a distance runner with a greater concentration of slow-twitch fibres and vice versa [20, p. 65].

Agonist and Antagonist

Every muscle in our body is matched by another muscle that can counteract its action. Taking the example of the biceps curl affecting a joint movement that brings upper and lower arm closer together, the m. biceps brachii is the agonist creating the joint movement (positive), the m. triceps brachii opposing this joint movement (negative) is the antagonist [27, p. 51]. If the movement triceps extension is performed the agonist-antagonist relation is reversed, i.e. the m. biceps brachii is the antagonist opposing elbow extension and the m. triceps brachii the agonist causing elbow extension. For a movement to be allowed, the antagonist must relax. A concurrently contraction of both agonist and antagonist stabilizes and slows the movement [20, p. 74].

2.2. Muscle action types

Muscle action results in movement and can be divided into different types that occurs.

2.2.1. Isotonic muscle action

Isotonic contraction (constant muscle tension) is only possbile over a small range under quasi-isometric conditions. Muscle tension will always vary since every movement involves acceleration or deceleration. More relevant for training is the auxotonic contraction, which refers to a muscle action involving changes in muscle tension and length. Additionally, dynamic muscle movement can occur while shortening (concentric) or lengthening (eccentric) the muscle [46, p. 114].

Concentric contraction

A concentric muscle action takes place if the muscle shortens while generating tension actively [28]. Hereby the net muscle forces have the same direction as the change in joint angle (positive-dynamic). An example is the biceps curl, respectively flexion of the arm to decrease the angle between the humerus and the forearm. Concentric contractions are used in exercise to generate forces against external resistances [20, p. 75].

Eccentric contraction

Increasing muscle length by external torque being greater than the muscle torque is known as eccentric muscle action [28]. The external component is usually the antagonist muscle group or gravity [27, p. 51]. The net muscle force acts in the opposite direction of the change in joint angle (negative-dynamic). An example is the lowering into a squat position whereby knee and hip extensors control the movement.

Eccentric muscle action exceeds the concentric muscle action strength due to the internal muscular friction. In concentric muscle action the sarcomeres have to work against an external force plus the internal muscle friction, whereby for eccentric muscle action it is the other way around. When a weight is moved through eccentric muscle action the external force has to overcome the internal muscle force plus internal muscle friction. So, the internal muscular friction decreases concentric strength and increases eccentric strength [7]. Another factor is the contribution of the elastic strain energy [31].

Isotonic training

Most exercises performed in fitness studios can be termed as isotonic training, whereby a constant external load is moved through the individuals range of motion (ROM). The movement is conducted through eccentric and concentric muscle action. The actual load of the muscle varies throughout the ROM as length-tension or force-velocity relation changes [20, pp. 89-90].

2.2.2. Isometric muscle action

Isometric contraction (constant muscle length) describes the joint angle, which remains constant. Internal muscle contraction will occur but does not result in a movement. Consequently it only occurs when the muscle force balances the resistance upon it without movement [46, p. 113].

Isometric training

The term isometric describes exercises which load the muscle in a static joint angle in a way that the muscle torque equals the resistance torque preventing movement to occur. Especially in medical rehabilitation isometric movements are used as they are easier to perform than concentric movements. The great disadvantage is that the muscle only strengthens in the specific joint position it is trained in lacking a continuous strength development throughout the full ROM [20, p. 89].

2.2.3. Isokinetic muscle action

Isokinetic contraction describes a movement with constant velocity and varying muscle tension. This term needs to be used carefully as it is very unlikely to contract the muscle at constant velocity over the full ROM. Constant velocity cannot occur over the full range of action, because an acceleration is always involved in beginning and ending the movement. Consequently isokinetic machines are not purely reflecting an isokinetic movement. The resistance of the machines increases in response to more muscle force, thus limiting the velocity of movement to roughly isokinetic conditions. So even if the external movement on an isokinetic machines follows a constant velocity, the underlying muscle contraction does not [46, p. 114].

Isokinetic training

This form of training can only be realized through specific machines, normally called isokinetic dynamometers, that can control movements through a ROM with a constant velocity and varying load. The user works against the resistance of the machine generating maximum tension against the specific lever arm speed, whereby the tension varies due to different leverage and muscular attachments throughout the ROM. Isokinetic testing for maximum strength has been established as a good measurement method in the laboratory because the total individual ROM can be tested in comparison with isometric testing [20, p. 90].

2.2.4. Comparison of isokinetic versus isotonic training

When comparing isokinetic training with conventional isotonic training *Golik-Peric et al.* (2011) found out that isokinetic training result in a greater strength gain than isotonic training. By testing knee extensors and flexors over a training period of 4 weeks the average strength gain of the isokinetic training protocol group accounted for about 26.57%. The group performing the isotonic training protocol also increased their strength, but to a lesser extent of about 12.87%. Furthermore the isokinetic training protocol restored imbalances of knee extensors and flexors more effectively than an isotonic training protocol [18]. The investigation was carried out with 38 young adults (mean age of 23.3 ± 3.6 years), which were split into two groups. One group followed a bilateral isokinetic training protocol for the knee extensor and flexors, the other group followed an isotonic training protocol in the form of half squats. Four weeks of training with 5 sessions per week, so in total 20 training sessions were performed by both groups. Repetitions ranged from 10-20 in the isokinetic group and from 4-20 in the isotonic group.

Another study by *Neha et al.* (2017) found out that isokinetic testing is the best way of strength testing and that the isokinetic strength training form improves strength maximally. The study was performed with 30 subjects split into 3 groups with different training protocols (isometric, isotonic, isokinetic). Post and pre test were made for all three forms of strength testing (isometric, isotonic, isokinetic). The improvements for each of the three forms of testing was maximum with its own training form. Meaning that the isotonic training group improved most in isotonic testing, the isometric training group in isometric testing and the isokinetic training group in isokinetic testing. But isokinetic training shows that strength improves to a great amount (gain of 47.16%) in its respective isokinetic strength testing compared to the other training forms (isotonic:

+23.75%, isometric: +14.93%) also tested upon isokinetic strength.
A further study with 20 men split into two groups, showed that the isokinetic group had higher muscle activity compared with the isotonic training group while performing exercises regarding the ankle joint [24].

2.2.5. Force-Velocity Relationship

The optimal muscle length is determined by a maximum overlap of myofilaments ensuring maximal numbers of cross-bridges that can be formed [20, pp. 82-83]. Consequently this length describes the possible maximum isometric force of the muscle. The force-velocity relationship hereby sets the speed of muscle contraction in relation with the maximum force at a given optimal muscle length [46, p. 24].
Hill (1938) proposed a force-velocity equation still used today [21]:

$$F = \frac{F_0 b - av}{b + v} \tag{2.1}$$

with:

F	maximal muscle force at optimal length [N]
F_0	maximal isometric force at optimal length [N]
v	muscle contraction speed [m/s]
a	coefficient for frictional resistance [N]
b	constant [m/s]

For concentric contractions the force-velocity relationship shows an inverse behaviour, i.e. the faster the muscle contracts the less force is generated and vice versa. The maximum force will be at zero velocity due to the forming of a large number of cross bridges. As velocity of muscle shortening increases the cycling rate of cross-bridges does too with fewer cross-bridges attached at the same time. Consequently maximum velocity is determined by cross-bridge cycling rates and whole-muscle fibre length over which shortening occurs [20, p. 79].

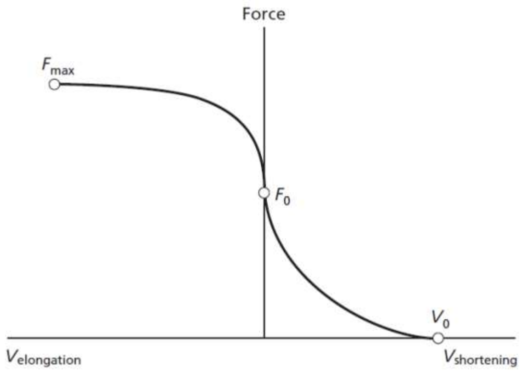


Figure 2.4: Schematic force-velocity relationship in the muscle; left part=eccentric muscle action, right part=concentric muscle action [46, p. 24]

In eccentric contractions the force increases with increasing speed of muscle lengthening, because the muscle is stretching as it contracts (see figure 2.4). Whereby maximum voluntary eccentric forces can exceed maximum isometric forces at gicen optimal length at average by a factor of 1.2 to 1.4 [19].

If this concept is applied to lifting an external weight some principles have to be understood. Muscle contraction happens with an active force to match the external load and specific velocity, i.e. a low load results in an increased speed of contraction, a high load results in a reduced velocity of contraction to adjust the active muscle force. At the beginning of lifting an external load the muscles have to generate a force greater than the weight. As the movement is initiated the force decreases while the weight is moving [20, pp. 70-80].

2.3. Muscular adaptation and training

Training has an effect on the effectiveness of muscles in different ways. By regularly repeating a movements the neuromuscular coordination is improved. Endurance training, i.e. a training with submaximal intensity over a long period of time increase the density of mitochondria and the oxidative capacity of slow twitch fibres. Strength training, respectively maximal shortening of muscle for a short period of time promotes a growth of muscle (hypertrophy) by increasing glycolytic capacity of the fast twitch muscle fibres [8, pp. 146-147]. This master's thesis focuses on the effects of strength training, whereby muscular adaptations are induced, which triggers an increase of muscular volume and results in a higher muscular strength. This process can be achieved through training against a resistance, i.e. lifting an external load or using gravity and the body weight [27, p. 269].

2.3.1. Hypertrophy and maximum strength

From the mechanical view, muscle strength is equal to the maximum isometric torque at a specific angle [20, p. 85]. The anatomical cross-sectional area (ACSA) is the area of the cross-section of a muscle perpendicular to its longitudinal axis, whereby the physiological cross-sectional area (PCSA) is the area of the cross-section of a muscle perpendicular to its fibres. The muscle force is proportional to the total number of myofilaments on the muscles PCSA, because more contractile elements can create more force upon muscle contraction [27, p. 70]. Training on muscle strength focuses on development of a greater PCSA and developing more tension per unit area of PCSA. This is associated with an increase in the size of muscle fibre diameter as more capillaries supply the muscle. That is caused by the myofibrils, which separate and increase in size [20, p. 85].
The Majority of studies were unable to show a correlation between maximal strength and fibre type composition, leaving the main determining factor for maximum strength being the muscle's volume [27, p. 60]. In the initial phase of strength training, especially for untrained persons neural adaptations are the main contributor to a strength gain. Most training studies does not exceed this phase. One study by *Akima et al.* [3] for instance shows improvement in isokinetic strength after short period (2 weeks) of isokinetic training. Though the ACSA of the M. quadriceps femur did not increase in the subjects, meaning that the increased muscle strength was mainly due to neural factors.

Figure 2.5 illustrate the strength progression and implies that in the long term hypertrophy takes over the neural adaptations to be the main contributor to strength gain until a plateau is reached [27, pp. 304-307].

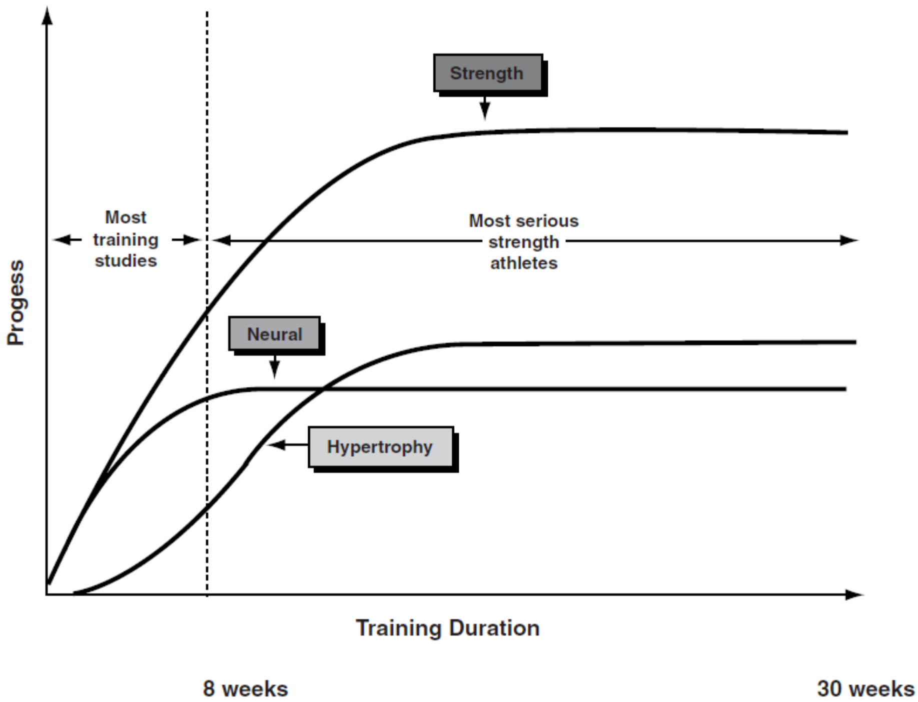


Figure 2.5: Muscular adaptation to strength training [20, p. 86]

Another important factor for strength development is the proper intensity as strength gains are directly related to muscle tension. The muscle only adapts upon an increased demand, meaning an overload of the muscle leads to higher strength, power and local muscular endurance [42].
In terms of progression an overload of the muscle can be accomplished through increasing the load with a fixed number of repetitions or increasing the number of repetitions with a fixed load. By training at a specific repetition range with a certain load an 2-10% increase can be considered when the person is able to exceed his current repetition range with a specific load by 1-2 repetitions [42]. Furthermore, altering repetition speed, decreasing rest period between sets or increasing volume are another options that can be considered. Those variables need to be changed and adapted over time to at least maintain but in the best case to advance specific training goals and avoid overtraining [29].

2.3.2. Training loading and repetition range

A training load can be determined by the calculation of a respective maximum amount of weight lifted for a specified number of repetitions, the repetition maximum (RM) or by using some percentage of the one repetition maximum (1RM). A certain repetition range and magnitude of load focuses on specific outcomes: **Muscular endurance** (low loads, >20 repetitions), **hypertrophy** (moderate loads, 8-15 repetitions), **maximum strength** (high loads, 3-8 repetitions), or **power** (high load, 1-3 repetitions). Nevertheless a blend of all training benefits are gained at any used repetition range, i.e. training with 12 repetitions at moderate load for hypertrophy will at the same time increase maximum strength, even though the effect is decreased compared to a specific maximum strength training at for instance a repetition number of 5 [4]. Especially for untrained or inexperienced persons a repetition range of 8-12 is recommended to obtain a neural training effect in learning the movement and prevent injury risk by avoiding high loads [42].

In conclusion strength training programs targeting muscular strength and hypertrophy best serve by moderate to heavy loads with a repetition range of 6-15RM [4]. A loading increase in a progressive manner should be intended in designing training programs to ensure muscular strength gains over a long period of time [42].

2.3.3. Prediction of one repetition maximum

Levinger et al. (2009) describes the one repetition maximum test as the gold standard assessing muscle strength in non-laboratory situations. It is widely used in training programs to calculate loading for different amount of repetitions. However, letting the user perform an one repetition maximum creates different issues. The injury risk is increased especially for the elderly and untrained on the ligaments and tendons, because of high forces [43, 13]. Another factor increasing the risk is performing a movement with maximum strength for the first time. Especially for the untrained a learning effect needs to be established first to let the body get used to the movement.

To provide relief it can be considered to establish a multiple repetition maximum measurement ranging from 3-7 repetitions. The equations in table 2.1 summarizes different equations for predicting a 1RM from a multiple RM with its respective weight.

	Prediction equations for a 1RM
Brzycki [6]	$1RM = \frac{100 \cdot load_{reps}}{102.78 - 2.78 \cdot reps}$
Epley [17]	$1RM = (1 + 0.033 \cdot reps) \cdot load_{reps}$
Lander [30]	$1RM = \frac{100 \cdot load_{reps}}{101.3 - 2.67123 \cdot reps}$
Mayhew [36]	$1RM = \frac{100 \cdot load_{reps}}{53.3 + 42.9 \cdot exp[-0.055 \cdot reps]}$
O'Connor [40]	$1RM = load_{reps} \cdot (1 + 0.025 \cdot reps)$
Wathan [45]	$1RM = \frac{100 \cdot load_{reps}}{48.8 + 53.8 \cdot exp[-0.075 \cdot reps]}$

Table 2.1: Different equations for a predicted 1RM

The variable *"reps"* is the abbreviation for repetition and the variable "$load_{reps}$" is the load used to perform those repetitions.
Knutzen et al. (1999) investigated the validity of different 1RM prediction equations shown in table 2.1, precisely repetitions-to-fatigue prediction equations on 11 machine lifts for 51 older adults (70.7 ± 6.1 years). The mechanical machines used in this study targets the lower body as well as the upper body. A comparison between predicted and measured 1RM was conducted, more precisely the prediction equations was calculated with a 7-10 repetition maximum. The correlations between actual and predicted 1RM values showed a moderate to strong relationship with a higher coefficient for upper (0.77-0.90) than lower body (0.61-0.80) exercises. No equation surpassed the others in terms of accuracy or strength of prediction. The prediction equations were used to calculate from a 7-10 RM to a measured 1RM. It is to note that the average predicted 1RM value was lower than the actual 1RM for all exercises and all prediction equations.

Another possibility proposed by *Reynolds et al.* (2006) used the free weight barbell bench press and the Cybex plate loaded leg press to determine a 1RM prediction equation. This study included anthropometric data like gender, age and resistance training volume. 70 subjects between the age of 18-69 years (36 women, 34 men) were tested. Their data analysis concluded that a 5RM is the most accurate prediction of maximum strength in comparison with a 10RM or 20RM test.
They formulated two non-linear prediction equations for the Chest Press and Leg Press and a linear equation using the 5RM. This study also compared their prediction equations with the equations in tabular 2.1 with additional equations.

		Formula predicted 1RM
nonlinear	**Reynolds Leg Press**	$1RM = \frac{load_{reps}}{0.7817 \cdot exp[-0.0569 \cdot reps] + 26.41}$
	Reynolds Chest Press	$1RM = \frac{load_{reps}}{0.5551 \cdot exp[-0.0723 \cdot reps] + 48.47}$
linear	**Reynolds Leg Press 5RM weight**	$1RM = (1.09703 + load_{5RM}) + 14.2546$
	Reynolds Chest Press 5RM weight	$1RM = (1.1307 + load_{5RM}) + 0.6998$
	Abadie [1]	$1RM = 7.24 + (1.05 \cdot load_{reps})$

Table 2.2: Reynolds 1RM prediction equation [43]

They found out that the most accurate equation to predict 1RM for the Leg Press are their own and the one of *Abadie and Wentworth* (2000). The most accurate prediction equation for Chest Press are their own and those of *Brzycki* (1993), and *O'Connor et al.* (1989). The accuracy of their own equation is explained by *Reynolds et al.* (2006) through the fact that the prediction equations need to be exercise specific. In this case two different equations are used for a Chest Press and a Leg Press exercise compared to the other studies that used one prediction equation for all exercises. Their prediction equations also show an inflated accuracy because they are based on the data which the equations were derived from.
For the next step they performed a cross validation to determine the test-retest reliability of their prediction equations using 20 different subjects. By examining the data all prediction equations mentioned before show a similar accuracy with a 5RM always being more superior in accuracy of the prediction equation compared to a 10RM.

An interesting issue is that the anthropometric variables (e.g. height, weight), as well as gender and training volumes, did not improve the prediction accuracy. *Reynolds et al.* (2006) concluded that either all the variables (e.g. age, gender, training volume) are unrelated to 1RM strength or that they are so interrelated to strength that a 5RM sufficiently take all the variables into account to display the proper 1RM strength. That fact is beneficial for calculating a 1RM as it is possible to apply a 5RM value to a prediction equation to get the accurate 1RM value without taking variables like age or gender into account.

In addition to this context a study by *Dohoney et al.* (2002) found out that a 4-6RM submaximal strength assessment is more accurate than a 7-10 RM strength assessment. It has to be noted that the investigations were done with 34 subjects by the age of 19-32 years, who had not done strength training within the last year before the beginning of the study.

3. Methodology

3.1. Road map

The road map will give an insight into the steps necessary to formulate a modular product variant for strength training machines on basis of the existing product series.

1. **Collecting data**
   Collecting raw data extracts from software milon Care [37] and material costs of single components from purchase department.

2. **Evaluation of biostatistical data**
   Evaluation of the raw performance data, ROMs and training positions to determine on the one hand which load is sufficient for the majority of user and on the other hand if the current adjustments for a physiological training position (e.g. range of motion, seating height) is appropriate for the majority of users.

3. **Component cost analysis**
   Identifying and defining generic component groups that are similar in all machines and facilitating further considerations.

4. **Define function of machine**
   Formulation of function with respect to the interaction of the machine with the user.

5. **Function cost analysis**
   Prioritizing defined functions and rate it in a matrix. Identification of cost drivers to show cost reducing potential with alternative components and concepts.

6. **Concept for alternative component groups**
   Concept development for component groups with the highest cost reducing potential.

7. **Evaluation of concepts**
   Conduction of a feasibility study and cost analysis for developed concepts.

8. **Platform development**
   Requirement formulation of new product series and differentiation from current series. Formulation of platform modules and distinctive features.

3.2. Company profile

The company milon industries GmbH develops and produces training machines with the focus on easy handling through automatically adjusting movement patterns and loads. Meaning that an electric motor generates the force which upon the athlete or patient works against. A further feature is the machines ability to self-adjust according to the users specific anthropometric data. Meaning that the sitting position and range of motion for every athlete is adjusted individually and therefore ensuring safe execution of the exercise.

The product portfolio consists of cardio machines and several strength training machines targeting specific muscle groups. In mechanical machines weight stacks are responsible for the resistance the user has to work against. The milon strength training machines uses the electric motor to generate that resistance. Furthermore they can inherit different training modes like increased eccentric and isokinetic training.

Milon operates in the business to business (B2B) market and targets fitness studios medical facilities, companies and hotels.

Due to the automatic adjustment features the milon training machines are most suitable for beginners. A further application area is for patients in medical rehabilitation centres. The guided movement pattern through the machine is especially beneficial for patients, who cannot perform coordinate difficult movements in therapy. milon is certified by the ISO 13485 and guideline for medical devices 93/42EWG and is one of the leading manufacturer in the segment of fully electronic training machines. Furthermore, milon provides services like advising fitness studios, marketing and financial services and coaching.

3.2.1. Product portfolio

The hardware product portfolio consists of strength and cardio machines. The current product series is called Q, which is also the common prefix for all the machines. The cardio machines are the Q Bike and the Q Crosstrainer. The strength training machines can be split into three batches (see table 3.1).

Batch number	Strength training machines
Batch 1	Q Leg Curl, Q Leg Extension, Q Chest Press, Q Seated Rowing, Q Abdominal Crunch, Q Back Extension
Batch 2	Q Lat Pulldown, Q Shoulder Press, Q Leg Press, Q Biceps Curl, Q Triceps Extension
Batch 3	Q Butterfly, Q Butterfly reverse, Q Abductor, Q Adductor, Rotator

Table 3.1: milon product portfolio strength training machines

The machines are distributed to gyms and rehabilitation centres as circle system. A standard strength endurance circle consists of the strength training machines from batch one, three Bikes and three Crosstrainers. Furthermore, the customer can choose the circle himself and for instance just use the strength training machines. As of 2th April 2019 Q free was introduced to the market. Every training machine can be run individually and is therefore not bound to the circle. The aim is for the customer to replace their mechanical training machines, because of the benefits of tracking training data and automatic adjustment by the milon machines.

The software product is called milon Care and is the comprehensive training and coaching software. It works cloud-based and ensures the proper functioning of the different training modes, the adjustment of machines and is furthermore used to acquire all user data. All training data and studio processes is combined in a connected training system (CTS). milon Care is used to manage the user data and it is possible to create and assign training programs [38]. Altogether it accompanies the hardware and helps the studio owner to most efficiently coach his customer.

3.2.2. Training Procedure

Prior to the first training the user will be measured through a machine called "Milonizer", which captures the users anthropometrical data, respectively the lengths of the extremities and the users ROM, for adjusting the right exercise position. Using algorithms default values are calculated to set the machines to the proper position for training. The coach or therapist will then fine adjust the training position and ROM together with the user for every machine.

Besides age, gender and height the user is also asked to state his training target, which can be hypertrophy, fat loss or reducing pain. The coach or therapist will also categorize

the user as beginner, intermediate or professional.
To determine the right load during exercise, a prior maximum strength measurement, the initial isokinetic measurement (IKM), is performed. The lever arm is moved through the whole individual ROM of the user. Depending on the machine the angle velocity ranges from 6°/s to 15°/s. Each machine has a angle velocity set, which the motor maintains. The force is calculated over the lever arm length from the torque the motor has to generate to maintain the respective angle velocity.
The IKM value is the basis for calculating the load during exercise for every user individually. All biostatistical data is generated and processed with the milon software CARE [37].

3.2.3. SWOT Analysis

The SWOT - analysis is used do evaluate a companies **S**trengths, **W**eaknesses, **O**pportunities and **T**hreats. It is a standard tool for planning product strategies [26, pp. 81-82]. The individual points will be described in short:

- *Strength*: What are the unique selling propositions (USPs) and what are benefits for the consumer compared with products from competitors?
- *Weaknesses*: Where does the competitors offer better benefits for the consumer?
- *Opportunities*: What new markets can be entered?
- *Threats*: Is the market big enough? How many competitors are in the market? Are there any risk for image damages?

Numbers and Trends

To examining opportunities and threats in the market a prior look on the health and fitness market as well as current trends is mandatory.
"The European Health and Fitness Report" by Europe Active and Deloitte includes data of the 28 European union member countries and additionally the countries Norway, Russia, Switzerland, Turkey and Ukraine. The current report as of 31.12.2018 shows that there was an increase by 2.9% in commercial net sales by the leading fitness equipment manufacturers comparing to the previous year. Market growth is primarily driven by the increase of fitness clubs by 4.6% to 61,984 across all countries, leading to a member gain of about 3.5% to 62.2 million [44].
To get an insight into sport and physical activity the European commission tasked TNS

Political & social network to conduct a survey in the 28 EU Member states, which was performed 2nd and 11th December 2017. A total number of 28031 EU citizens from around 28 EU member states were interviewed face-to-face in their native language. The main findings were, that about 40% of Europeans exercise or play sport at least once a weak. It is to note that at this survey the term "exercise" was not specified and therefore could be subjectively interpreted by the individuals. The interpretation can range from performing excessive strength training to walking at a moderate pace. The main reasons for exercising or doing sports were declared to be improving health (54%) and fitness (47%), relaxing (38%), having fun (30%) and improving physical performance (28%). Lack of time is by far the main reason given for not practising sport more regularly (40%). [12].

The fitness industry is trend driven and the Deutscher Sportstudio Verband (DSSV) reports annually about upcoming trends [14]. The top five trends from this investigation in descending order are:

1. Qualified and highly educated coaches
2. Training programs for the elderly
3. Measurement and documentation of exercise
4. Corporate health management
5. Health coaching

Results

The results of the SWOT analysis are recapped in Figure 3.1. The great interlocking of the hardware, electric engine and the software is a USP for this product besides its user friendly handling. In combination with the comprehensive concept of well educated coaches the upcoming trends could be satisfied. Nevertheless there are more opportunities to expand in existing markets and enter new markets. With demographic change and the increasing health awareness a big market will be created.

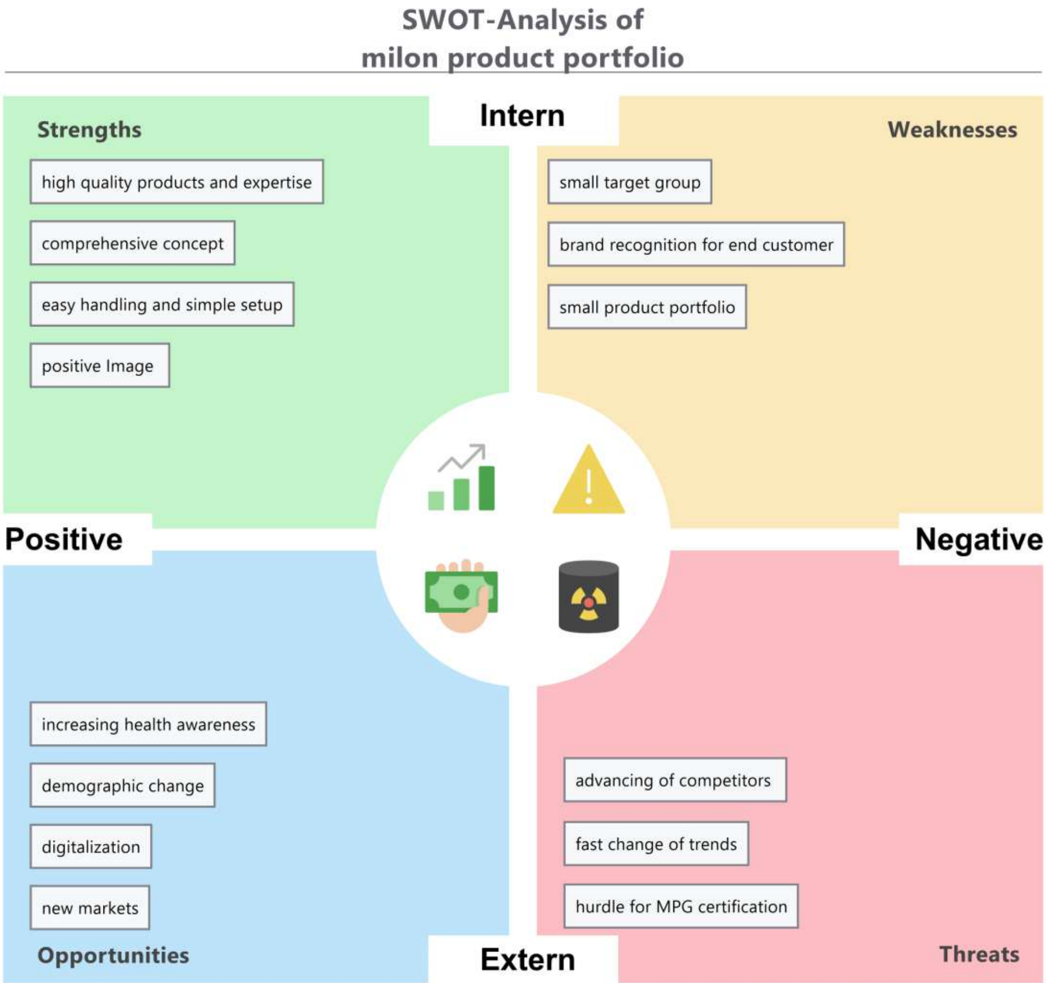


Figure 3.1: Result of Swot Analysis[2]

There is a great potential for milon to involve a larger target group by expanding its product portfolio. The aim is to acquire new customers by using the existing concepts and penetrate the new market with a lower price range. The current training studios purchasing milon machines can be categorized at a high price monthly fee for their customers. Another market for the current series are rehabilitation centres, whereby each machines has to fulfil the requirements of the Medizinproduktegesetz (MPG). The new series targets the market of training studio in the upper mid range. To create differentiation from the current series rehabilitation centres will not be targeted as market. Furthermore, the MPG certification each machine had to pass would be too

[2]created with Mindjet Manager 2019 as of 28th March 2019

cost-intensive.

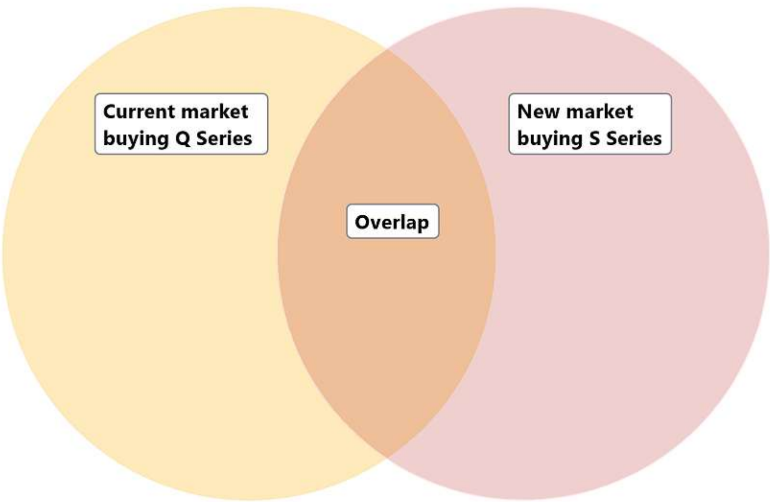


Figure 3.2: Illustration of market shares[3]

It is therefore important that both series does not cannibalize each other, i.e. taking away market share from another. The best case scenario will be a small overlap (see figure 3.2) with a greater amount expanding into a new market.

[3]created with Mindjet Manager 2019 as of 5th June 2019

3.3. Evaluation of biostatistical data

The data analysis were performed for eleven strength training machines of the Q series (batch 1 and 2) in total. The following chapters show a detailed analysis for the Q Leg Curl, Q Leg Extension, Q Chest Press, Q Seated Rowing, Q Abdominal Crunch, and Q Back Extension. Due to the market product launch of batch 1 in the first quarter of 2017 enough data sets were generated to get valid evaluations. Further the focus is on developing concepts for the strength training machines of batch 1.
Nevertheless the diagrams for the batch 2 strength machines Q Lat Pulldown, Q Shoulder Press, Q Leg Press, Q Biceps Curl, and Q Triceps Extension were also evaluated and can be found in the appendix (see chapter A.1).

3.3.1. Raw Data sets

The data extractions provided raw data sets from all users training on the Q circuit system (see figure 3.3.1). The Q free system and all test data were excluded from this analysis. The JavaScript Object Notation (JSON) files provided by milon CARE were transferred into Microsoft Excel and following parameter sets could be read out.

	A	B	C	D	E	F	G	H	I
1	uid	t	aw	adw	rom_start	rom_end	ikm	servo1	servo2
2	b0[redacted]	1551694954	11	12	18	89	42	64	30
3	B0[redacted]	1533278332	11	13	17	85	47	47	35
4	B0[redacted]	1490771311	11	14	16	88	44	52	48
5	B0[redacted]	1542904755	6	7	17	89	27	69	25
6	B0[redacted]	1551458210	20	29	11	96	56	57	42
7	b0[redacted]	1510600593	22	28	16	92	60	51	39
8	B0[redacted]	1515512581	28	33	6	96	94	44	71
9	B0[redacted]	1539086623	11	14	16	89	48	64	36
10	B0[redacted]	1522142092	18	23	16	94	52	55	59
11	B0[redacted]	1516171779	19	24	16	92	33	54	55
12	B0[redacted]	1549953996	27	37	16	92	62	40	49
13	b0[redacted]	1510040162	23	27	19	100	46	0	100
14	b0[redacted]	1549907274	15	19	17	89	45	60	34
15	B0[redacted]	1534409188	24	31	18	86	43	54	27
16	b0[redacted]	1551169173	14	18	18	88	29	86	0
17	B0[redacted]	1526491579	15	18	5	88	52	69	39
18	B0[redacted]	1515691110	11	13	16	92	25	62	10
19	b0[redacted]	1551694009	15	19	17	91	23	63	31
20	b0[redacted]	1524051294	14	17	11	89	48	66	12

Figure 3.3: Raw Data set read into Microsoft Excel[4]

The variables, which make up the first row of the data extract, are explained below.

[4]created with Microsoft Excel based on source: milon Care data extraction as of 5th march 2019

uid the individual user ID

t date of last training/log-out displayed as unix timestamp (representation as seconds from a defined unix epoche time)

aw last recorded concentric weight setting

adw last recorded eccentric weight setting

rom_start starting position of for performing concentric movement on the particular training machine

rom_start end position of user after finishing concentric movement and reversal point for starting eccentric movement

ikm most recent initial strength measurement maximum value

servo1 relate to machines seating and/or lever arm adjustment depending on particular machine

servo2 depending on particular machine a second adjustment is existent

While sighting the raw data sets it was discovered that several data sets were illogical. Transmission errors to the cloud at log-out can be identified as source for blank or inapplicable values. Another issue to mention is that the data can also inherit values for testing purposes and not actual weight, servo, ROM settings. Meaning that a user with authorization (e.g. coach, studio admin) can adjust values on the machine without training with those adjustments. Due to the amount of data sets, this case is assumed to have little impact on the entirety of the analysis.
Following errors where detected and affected data sets were filtered out:

- blank values regardless of array
- maximum strength value greater than maximum training load of machine
- maximum strength value lower than training load value
- eccentric load value lower than concentric load value (not applicable setting)

3.3.2. Data analysis

After filtering the raw data sets evaluable data sets for every strength training machine were obtained. Analyses for maximum strength value, eccentric and concentric training weights, ROM and servo-settings were performed. Following questions are answered upon evaluating the biostatistical data form Care:

- What are the maximum values in the maximum isokinetic strength testing for all users per strength machine?
- How are the training loads compared to the maximum load value from the strength test?
- Are the ROMs and the servo-settings suitable for the users to train in a physiological position?

The goal is to analyse the extent with which the users train on the milon strength training machines. Meaning which loads are reached in the maximum strength test and which loads are used for training. Furthermore, a statement should be made in which range of motions the users train. Ultimately the issue should be displayed at which extent the user train on the strength training machines.

General remarks on the diagrams

To describe the structure of the created diagrams figure 3.4 can be used as an example. The y-axis of the diagram describes the amount of user to corresponding weight setting. The x-axis describes the range of weight settings possible. One dot in the diagram describes the amount of user with that particular weight setting.
For the IKM, eccentric and concentric weight diagrams the 95th, 97.5th, 99th, 99.5th percentiles are used and displayed as straight vertical lines.
For the servo setting diagrams an average vertical line at setting 50 was implemented to better visualize any displacements of the curve (e.g. figure 3.8).
The ROM setting diagrams do not contain percentiles, but two different categories of data. The ROM start setting is described by the blue data points, the ROM end settings by the orange data points (e.g. figure 3.12). An issue for the ROM and servo setting diagrams that has to be explained are default values. That are values, which are calculated after the user is measured with the Milonizer. If the coach does not fine adjust those values they get saved unaltered. Because the extremities length of humans

follow a Gaussian distribution there is the possibility that outliers occur for the ROM setting diagrams.

3.3.3. Data evaluation Q Leg Curl

The Q Leg Curl is used in a seated position with the user's thighs fixated while he performs a knee flexion. The machine mainly targets the m. biceps femoris as well as the m. semimembranosus and m. semitendinosus.
The raw data set consisted of 132591 line of data, i.e. amount of user. After filtering the data set relating to requirements in chapter 3.3.1 a total amount of 126552 evaluable data sets remained.

Maximum strength value

The machine's maximum load of 100 kg is reached by 47 user (see figure 3.4). The curve is right skewed (M = 38.61 ± 15.81 kg), which is confirmed by the Median (Mdn) being smaller than the average value (Mdn = 36.00 kg).

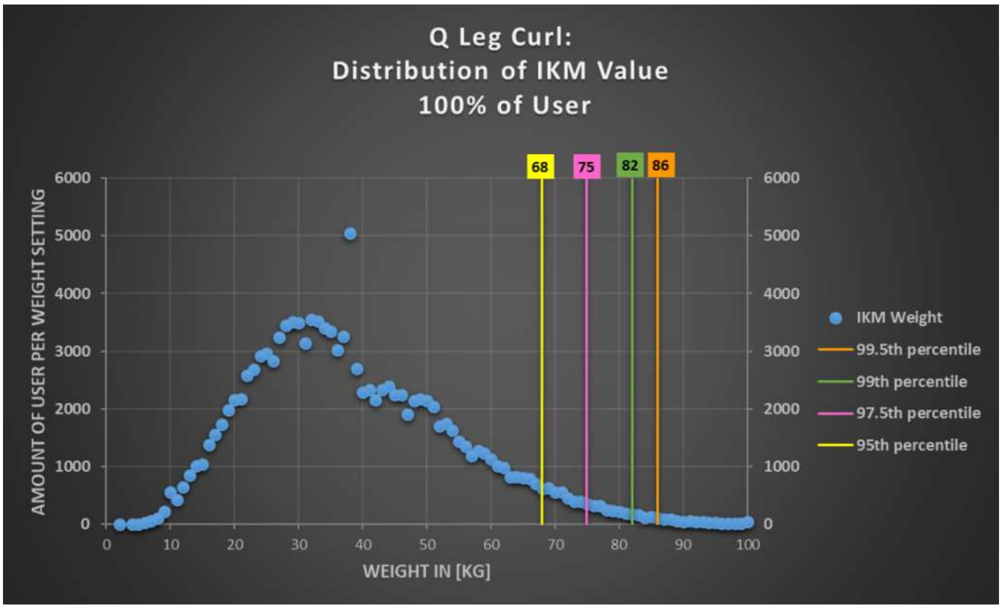


Figure 3.4: Maximum strength distribution Q Leg Curl[5]

[5]created with Microsoft Excel based on source: milon Care data extraction as of 5th march 2019

Concentric and Eccentric weight

No user actually trains with the maximum training weight setting of the machine for concentric or eccentric training weight (figure 3.5 and figure 3.6). The maximum value of 63 kg for concentric training weight is reached by one user.

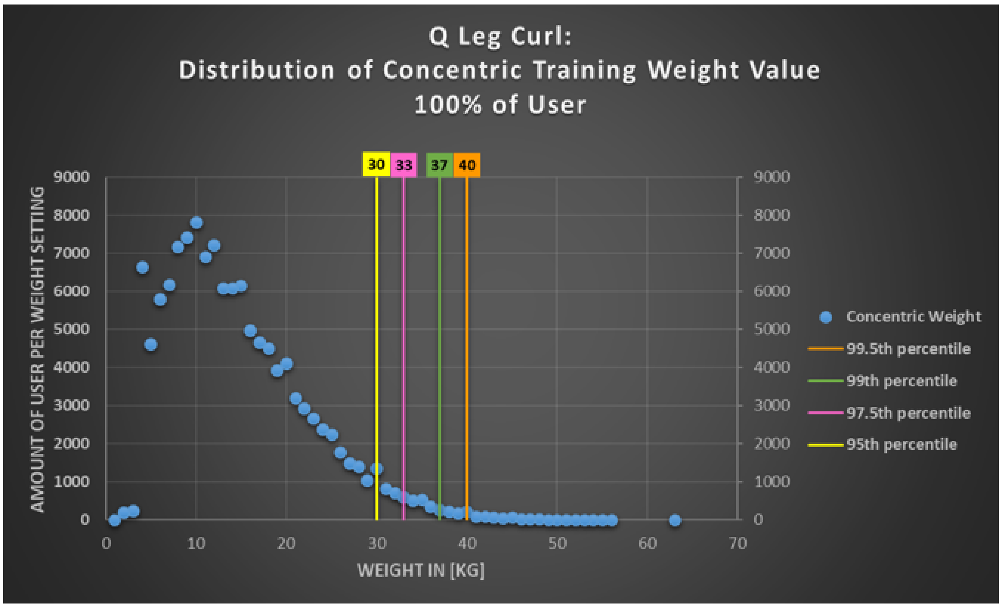


Figure 3.5: Concentric training weight distribution Q Leg Curl[6]

The maximum value of 84 kg for eccentric training weight is also reached by one user. The concentric weight setting curve (M = 14.48 ± 7.76 kg, Mdn = 13.00 kg) is like the eccentric weight setting curve (M = 17.97 ± 10.22 kg, Mdn = 16.00 kg) right skewed.

[6]created with Microsoft Excel based on source: milon Care data extraction as of 5th March 2019

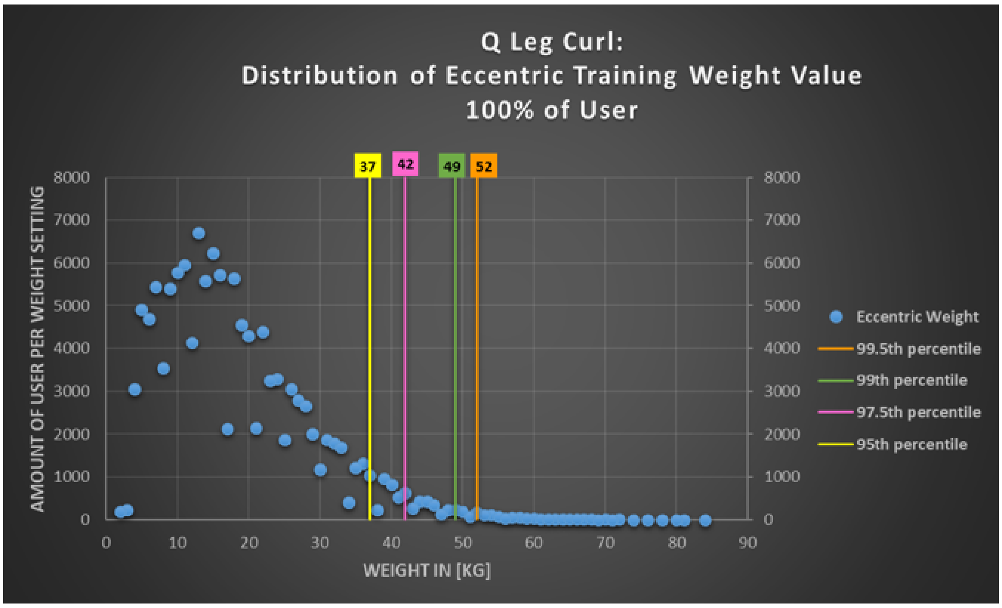


Figure 3.6: Eccentric training weight distribution Q Leg Curl[7]

The user's actual training weight is compared to the user's individual maximum strength value obtained from the isokinetic maximum strength test. Thereby the percentage of the concentric training weight with respect to the user's individual maximum strength value is M = 37.40 ± 12.75 % and for eccentric training weight is M = 45.99 ± 16.90 %.

[7]created with Microsoft Excel based on source: milon Care data extraction as of 5th March 2019

Servo settings

The first servo setting of the Q Leg Curl is the adjustment for the back support of the seating structure (see figure 3.8). The 0-direction is the most outer position and suitable for user with long thighs. The 100-direction is the position for the back support to be at the very front, which is suitable for persons with short thighs.

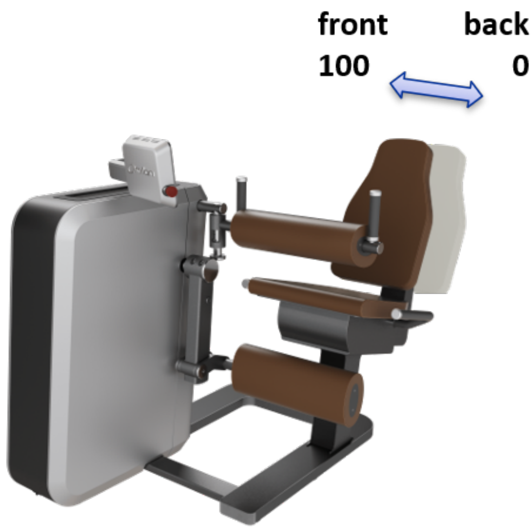


Figure 3.7: Servo1-Setting illustration Q Leg Curl: Back support adjustment[8]

The distribution of the curve shows that despite being slightly shifted to the right from the center (= 50) the full range is used (figure 3.8). There is an outlier at setting 26 and 60, both being default settings after measurement with the milonizer. It can furthermore be observed that there are outliers at setting 0 and 100. Meaning that a further adjustment is desired by the users (e.g. -10 or +110 setting value), but a wider adjustment range is restricted by the machine.

[8] edited figure retrieved from: R&D department milon industries GmbH, rendering with KeyShot by Luxion as of 21th December 2016

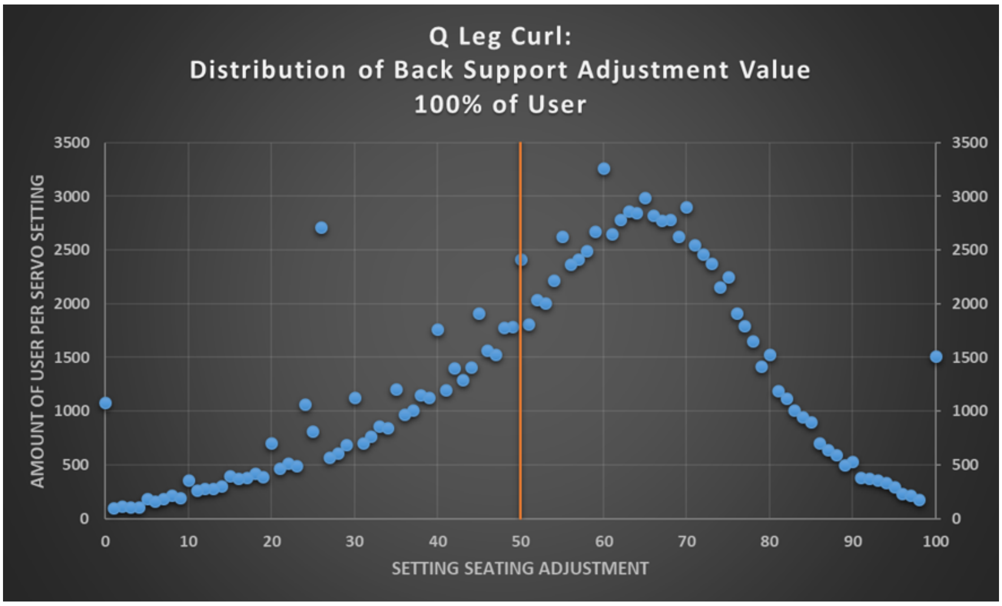


Figure 3.8: Back support adjustment distribution of Q Leg Curl[9]

The second servo setting of the Q Leg Curl is the adjustment for lever arm length and the principle can be seen in figure 3.9.

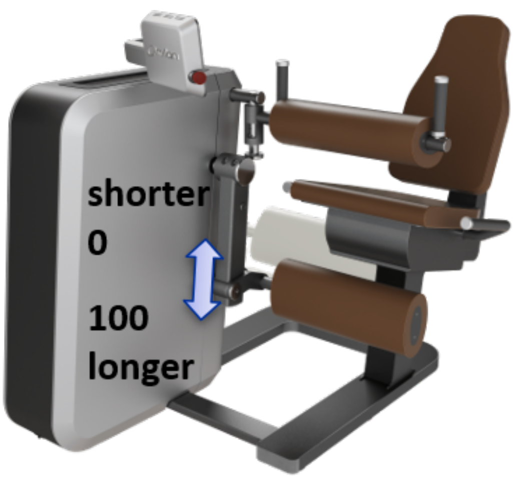


Figure 3.9: Servo2-Setting illustration Q Leg Curl: Lever arm adjustment[10]

The curve obtained from the diagram in figure 3.10 is shifted to the left from the center.

[9]created with Microsoft Excel based on source: milon Care data extraction as of 5th March 2019
[10]edited figure retrieved from: R&D department milon industries GmbH, rendering with KeyShot by Luxion as of 21th December 2016

There is an outlier at setting 30 being the default value. But more interestingly a further greater outlier at 0-setting can be obtained.

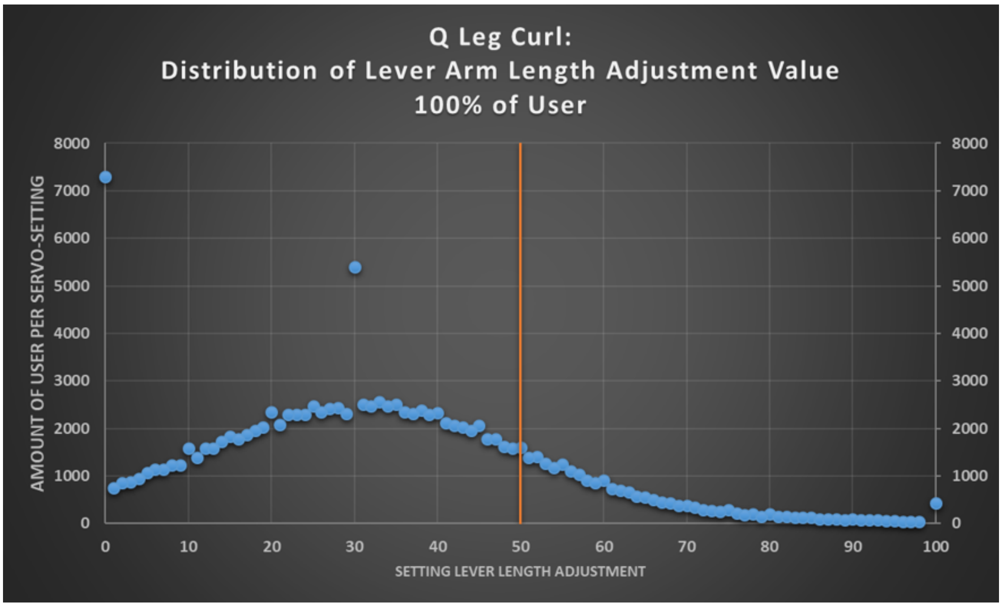


Figure 3.10: Lever arm length adjustment distribution of Q Leg Curl[11]

ROM settings

(a) ROM start

(b) ROM end

Figure 3.11: ROM illustration of Q Leg Curl[12]

[11] created with Microsoft Excel based on source: milon Care data extraction as of 5th March 2019

[12] edited figure retrieved from: R&D department milon industries GmbH, Software Poser as of 9th December 2016

The start position is with straight legs (figure 3.11a), whereby the end position is with bend knees (figure 3.11b).
As can be obtained from the distribution of figure 3.12 the current range of ROM setting is fully used. The outliers at settings 16 and 90 are default values. The outlier at setting 100 is of interest describing that many user can reach the end position with bend knees.

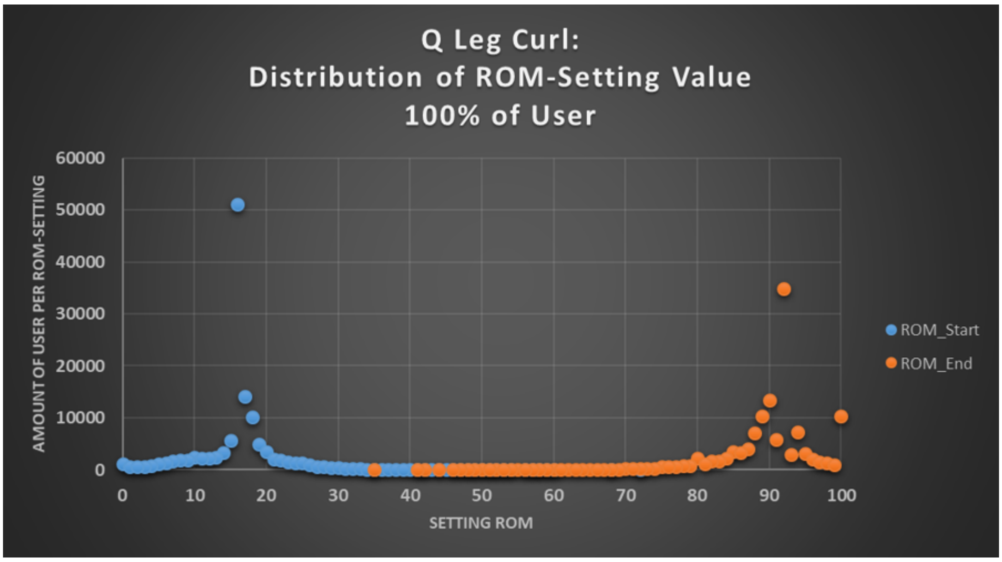


Figure 3.12: ROM distribution of Q Leg Curl[13]

Conclusion

According to the IKM curve distribution the maximum load of the machine is sufficient. When looking at the back support the adjustment range need to be expanded. The lever arm length adjustment should be shifted more towards the 0-setting or the lever arm should be constructed shorter.

3.3.4. Data evaluation Q Leg Extension

The Q Leg Extension is used in a seated position with the user performing a knee extension using grips on the side of the seat structure to assist stabilization. The machine mainly targets the m. quadriceps femoris and is performed in a seated position. The raw data set consisted of 124392 line of data, i.e. amount of user. After filtering relating to requirements in chapter 3.3.1 a total of 109827 evaluable data sets remained.

[13]created with Microsoft Excel based on source: milon Care data extraction as of 5th March 2019

Maximum strength value

1462 user reach the maximum load of the machine, which accounts for 100 kg (see figure 3.13). It is to note that the machine is limited to 100 kg and a potential maximum strength value of over 100 kg is not recorded even if the user would be able to exceed this limit. The isokinetic strength measurement is designed in a way that the machine's lever arm maintains a certain angle velocity while the user works against the resistance. If the user exceed the maximum load the lever arm would move faster. Another outlier is at weight setting 14 kg reached by 5925 user (5.39 %). The curve is right skewed (M = 39.55 ± 21.51 kg), which is confirmed by the median (Mdn = 35.00 kg) being smaller than the average value.

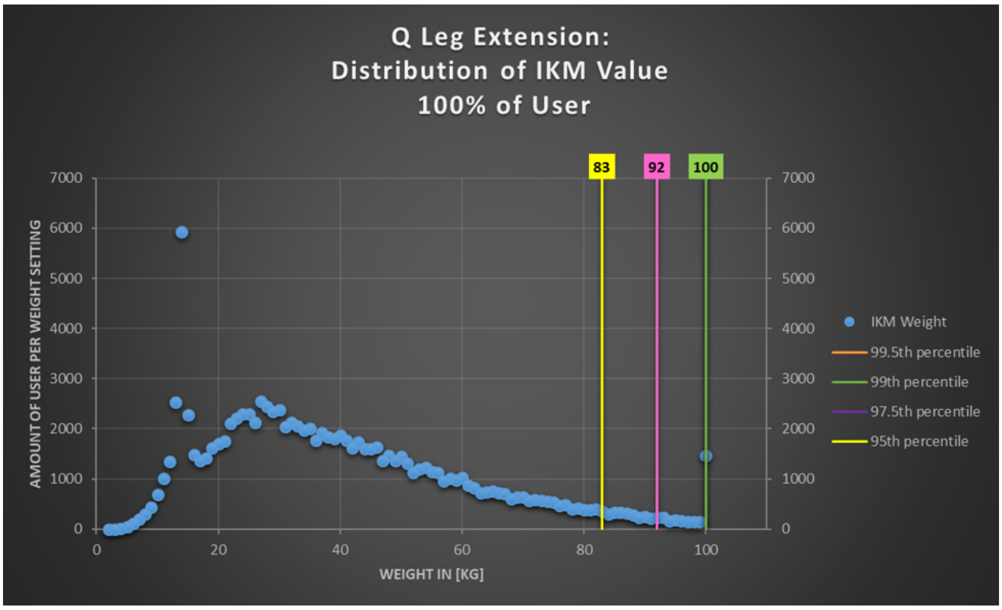


Figure 3.13: Maximum strength distribution Q Leg Extension[14]

Concentric and Eccentric weight

No user actually trains with the maximum training weight setting of the machine for concentric training weight (figure 3.14). The maximum value of 77 kg for concentric training weight is reached by one user.

[14]created with Microsoft Excel based on source: milon Care data extraction as of 5th March 2019

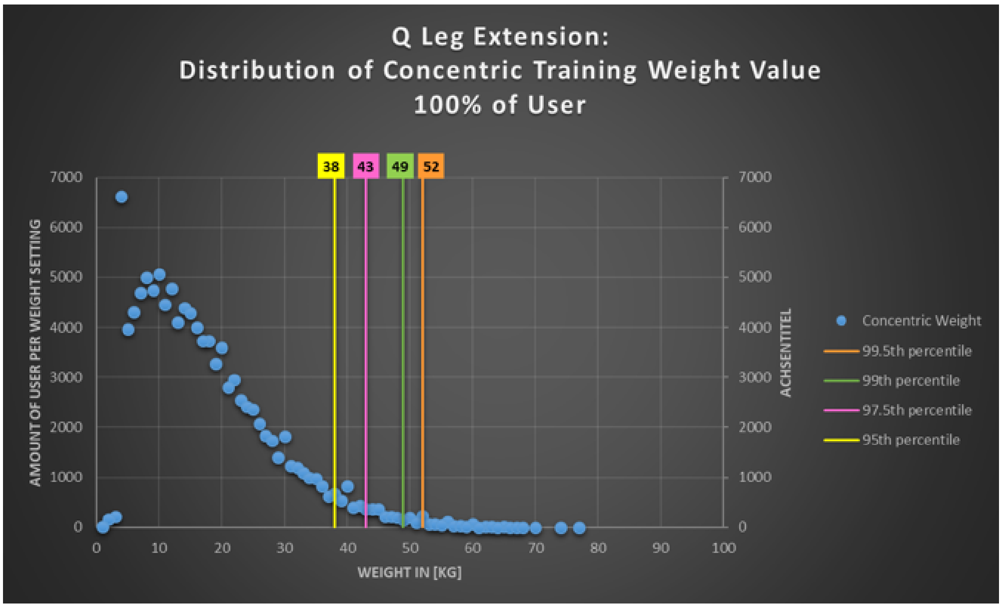


Figure 3.14: Concentric training weight distribution Q Leg Extension[15]

One user trains with the maximum weight setting for eccentric training weight (see figure 3.15).

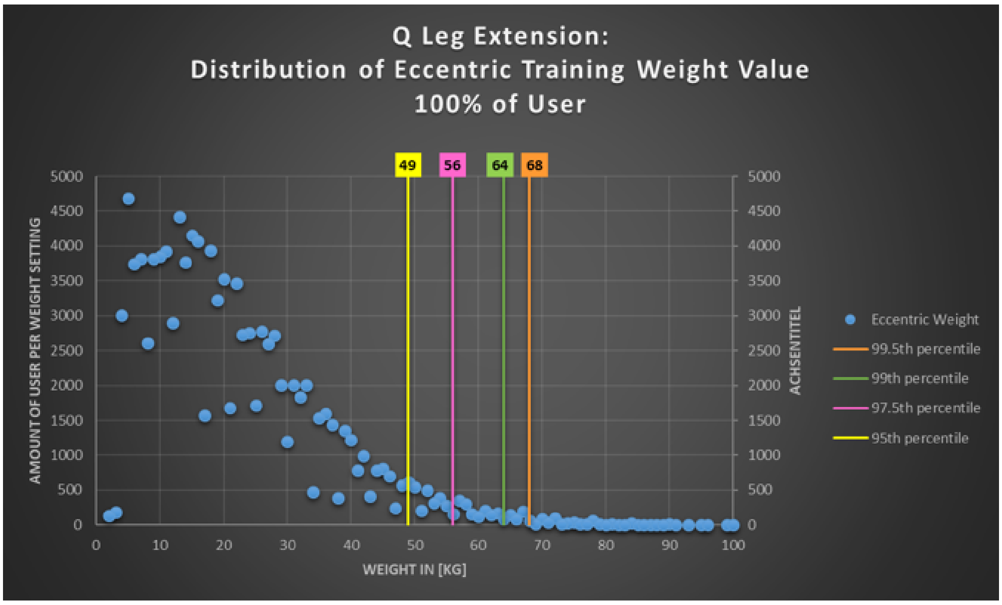


Figure 3.15: Eccentric training weight distribution Q Leg Extension[16]

The concentric weight setting curve (M = 17.20 ± 10.50 kg, Mdn = 15.00 kg) is like the eccentric weight setting curve (M = 21.51 ± 13.75 kg, Mdn = 19.00 kg) right skewed.

[15]created with Microsoft Excel based on source: milon Care data extraction as of 5th March 2019
[16]created with Microsoft Excel based on source: milon Care data extraction as of 5th March 2019

When comparing the user's actual training weight with the user's individual maximum strength value from the isokinetic maximum strength test, the percentage of the concentric training weight value with respect to the user's individual maximum strength value accounts for M = 44.10 ± 14.03 % whereby with respect to the eccentric training weight value it is M = 54.34 ± 17.98 %.

Servo settings

The first servo setting of the Leg Extension is the adjustment for the back support of the seating structure (see figure 3.16). The 0-direction is the most outer position and suitable for user with long thighs. The 100-direction is the position for the back support to be at the very front, which is suitable for persons with short thighs.

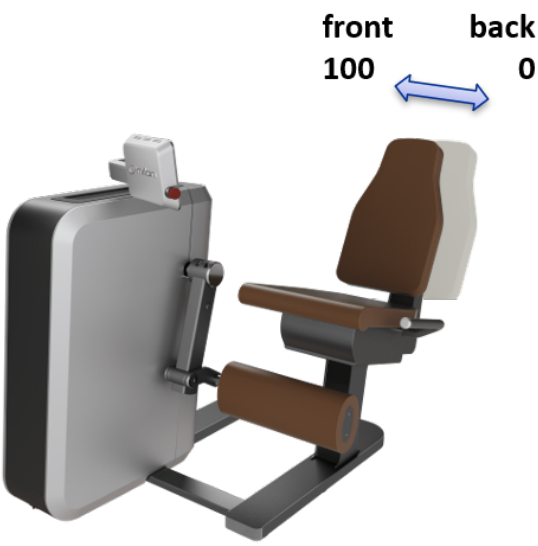


Figure 3.16: Servo1-Setting illustration Q Leg Extension: Back support adjustment[17]

The distribution shows that differently to the Q Leg Curl (figure 3.8) the curve is shifted to the left from center (= 50). The full range for this servo-setting is used and there is an outlier at setting 0 (figure 3.17).

[17]edited figure retrieved from: R&D department milon industries GmbH, rendering with KeyShot by Luxion as of 21th December 2016

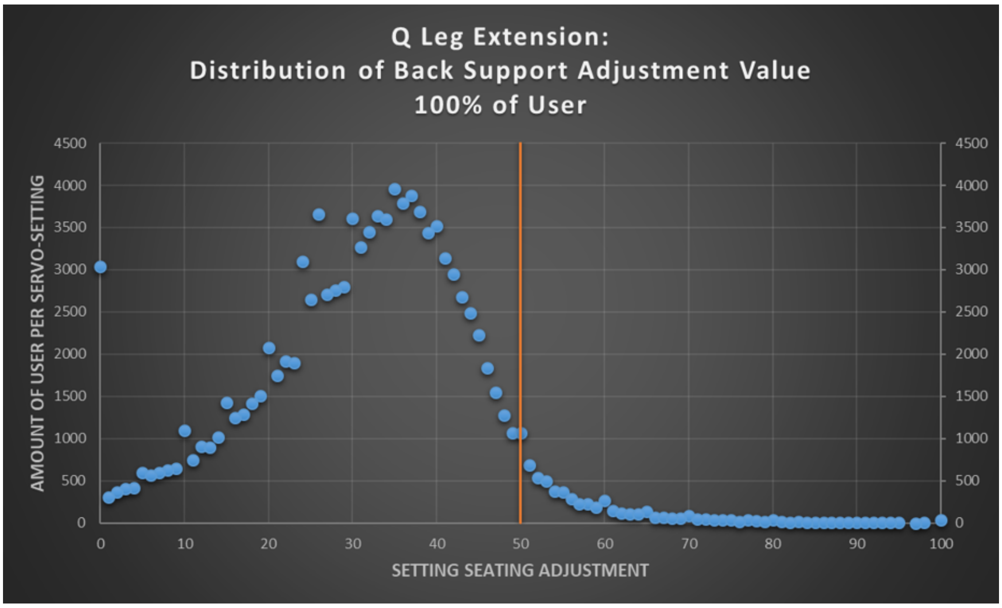


Figure 3.17: Back support adjustment distribution of Q Leg Extension[18]

The second servo setting of the Q Leg Extension is the adjustment for lever arm length and the principle can be seen in figure 3.18.

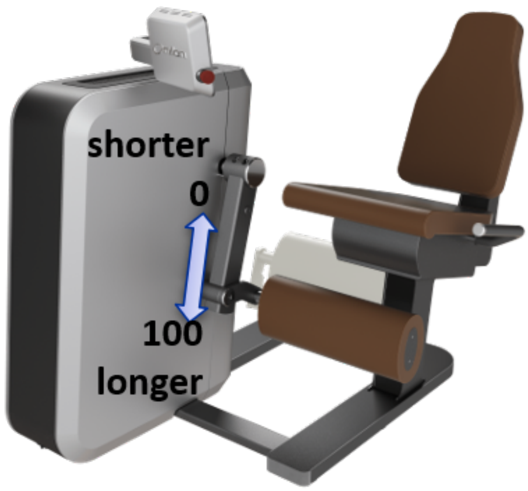


Figure 3.18: Servo2-Setting illustration Q Leg Extension: Lever arm adjustment[19]

The curve obtained from the diagram is shifted to the left from the center. There is an

[18]created with Microsoft Excel based on source: milon Care data extraction as of 5th March 2019

[19]edited figure retrieved from: R&D department milon industries GmbH, rendering with KeyShot by Luxion as of 21th December 2016

outlier at setting 20 being the default value. The outlier at 0-setting is of also of great interest (figure 3.19). Both outliers showing that a shift to the zero position is desired.

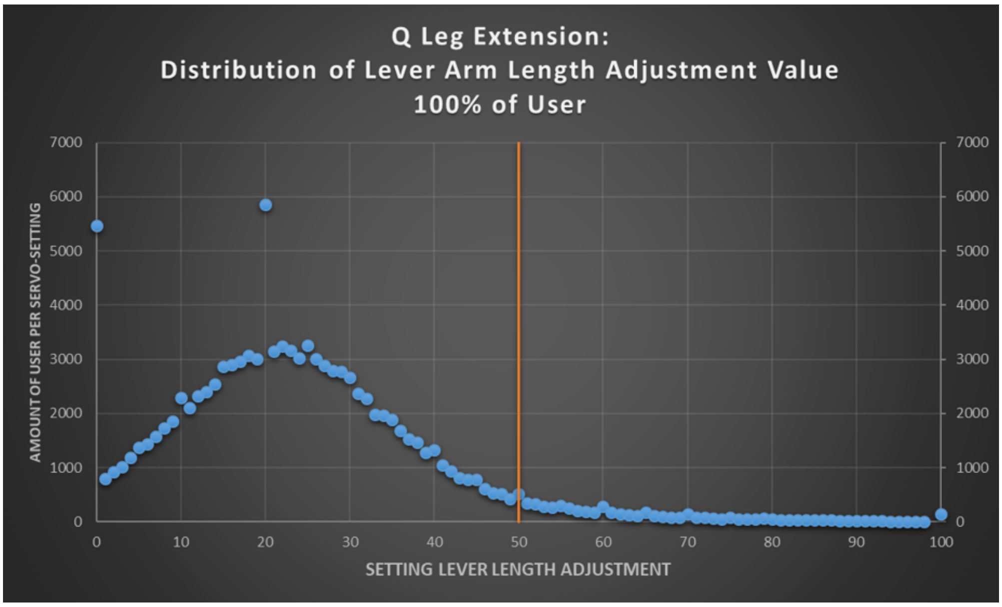
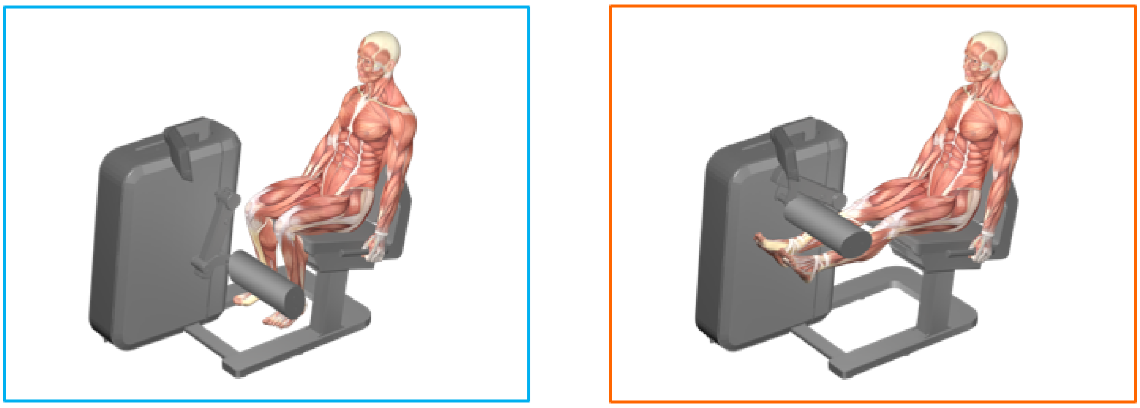


Figure 3.19: Lever arm length adjustment distribution of Q Leg Extension[20]

ROM settings



(a) ROM start (b) ROM end

Figure 3.20: ROM illustration of Q Leg Extension[21]

[20] created with Microsoft Excel based on source: milon Care data extraction as of 5th March 2019
[21] edited figure retrieved from: R&D department milon industries GmbH, Software Poser as of 9th December 2016

The start position is with straight legs (figure 3.20a), whereby the end position is with bend knees (figure 3.20b).
As can be obtained from the distribution of figure 3.21 the current range of ROM setting is fully used. The outliers at settings 18 and 92 are default values.

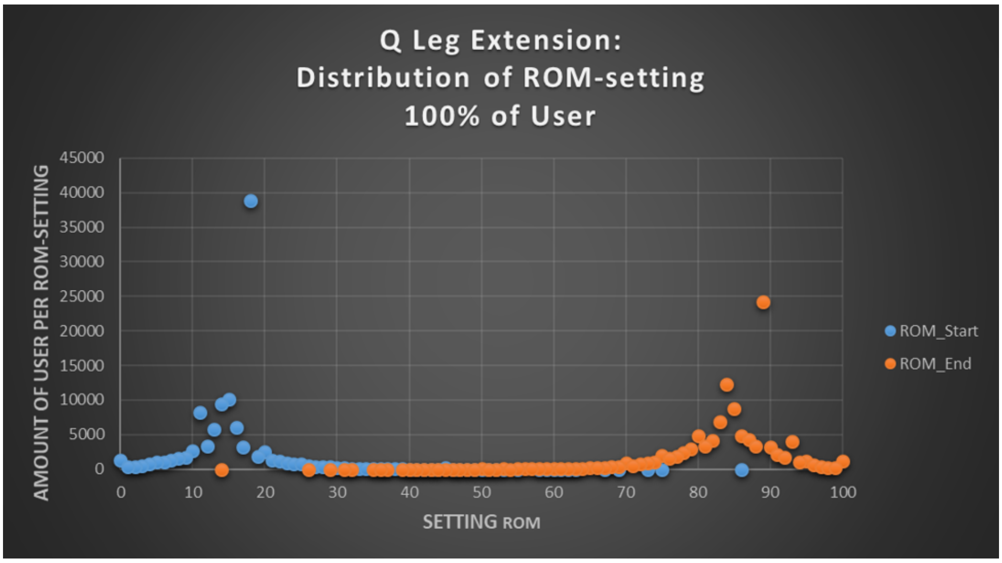


Figure 3.21: ROM distribution of Q Leg Extension[22]

Conclusion

Taking the outliers at maximum load value of the IKM curve into account an increase of maximum load can be considered if the isokinetic parameters remain unchanged (see chapter 3.2.2). Similarly to the Q Leg Curl the lever arm length needs to be shorter or shifted towards the 0-setting. The back support adjustment range needs to be expanded or shifted into the back position (0-setting).
Comparing the back support adjustment of the Q Leg Curl and Q Leg Extension one would assume similar distribution curves as the seating position relative to the lever arm is the same. It can be obtained that the curve for the Q Leg Curl is shifted to the 100-setting meaning that the majority of users are more likely to sit towards the front. Whereby the curve for the Q Leg Extension is shifted more to the 0-setting showing that the majority of users sit more towards the back. One possible explanation is that when training one the Q Leg Extension the users tend to additionally use their hips to generate more force. That can lead to the lower back coming forward and at the same

[22]created with Microsoft Excel based on source: milon Care data extraction as of 5th March 2019

time the upper back leaning more backwards. Both actions contributing into shifting the knee forward and the need for the back support to be adjusted more towards the 0-setting. Although the initial seating position setting is stored with the entire back having contact with the back support, an adjustment of seating positions can always be done afterwards by the trainer upon request of the user.

3.3.5. Data evaluation Q Chest Press

The Q Chest Press is used in a seated position and mainly targets the m. pectoralis major with support of m. triceps brachii, m. delotideus, m. serratus anterior and m. anconaeus.
The raw data set consisted of 146330 line of data, i.e. amount of user. After filtering relating to requirements in chapter 3.3.1 a total number of 142150 evaluable data sets remained.

Maximum strength value

As can be obtained from figure 3.22 no user reach the machine's maximum load of 170 kg in the isokinetic strength measurement. The maximum weight value reached by one user is 144 kg. The curve is right skewed (M = 56.32 ± 22.70 kg), which is confirmed by the median (Mdn = 54.00 kg) being smaller than the average value.

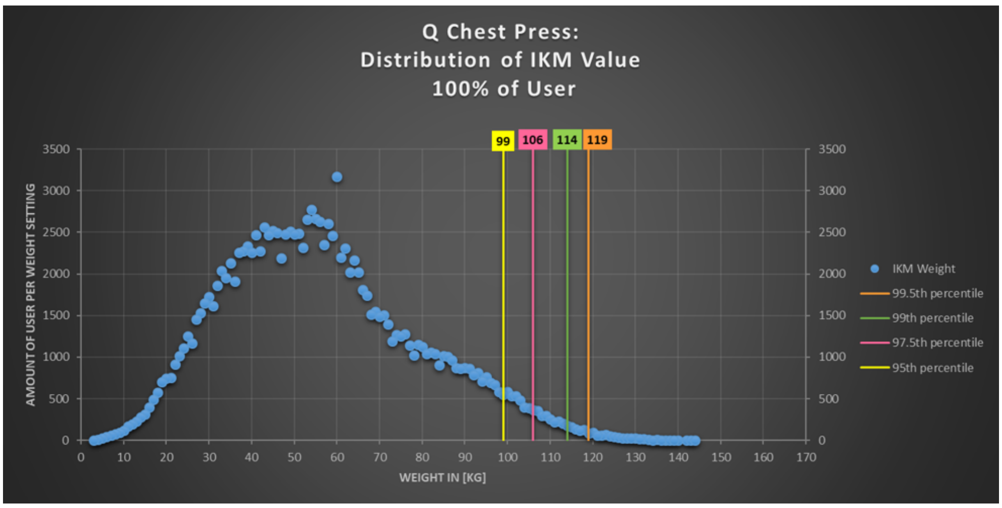


Figure 3.22: Maximum strength distribution Q Chest Press[23]

[23]created with Microsoft Excel based on source: milon Care data extraction as of 5th March 2019

Concentric and Eccentric weight

Consequently no user actually trains with the maximum training weight setting of the machine for concentric or eccentric training weight (figure 3.23 and figure 3.24). The maximum value of 95 kg for concentric training weight is reached by one user.

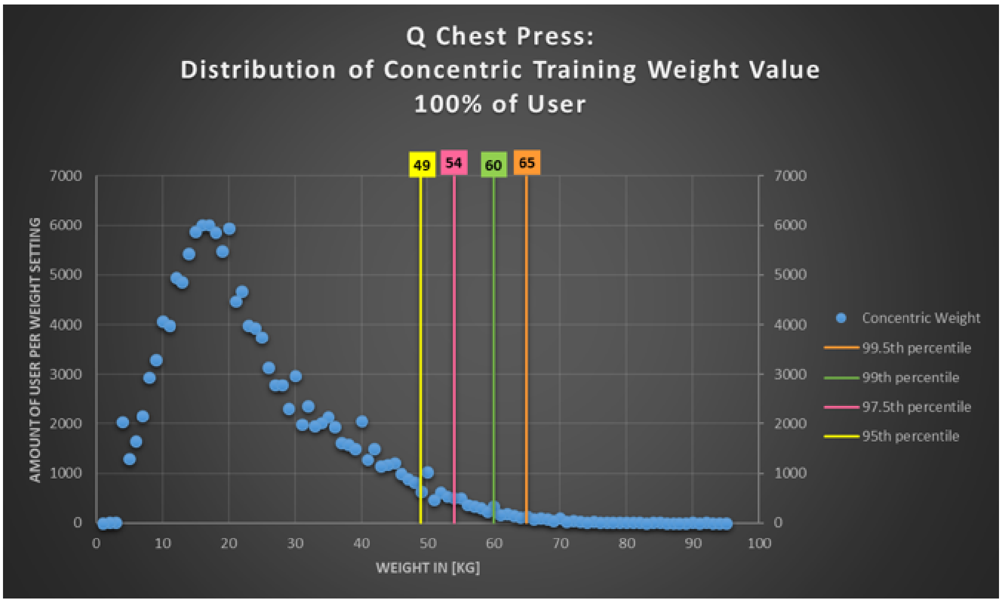


Figure 3.23: Concentric training weight distribution Q Chest Press[24]

The maximum value of 122 kg for eccentric training weight is also reached by one user.

[24]created with Microsoft Excel based on source: milon Care data extraction as of 5th March 2019

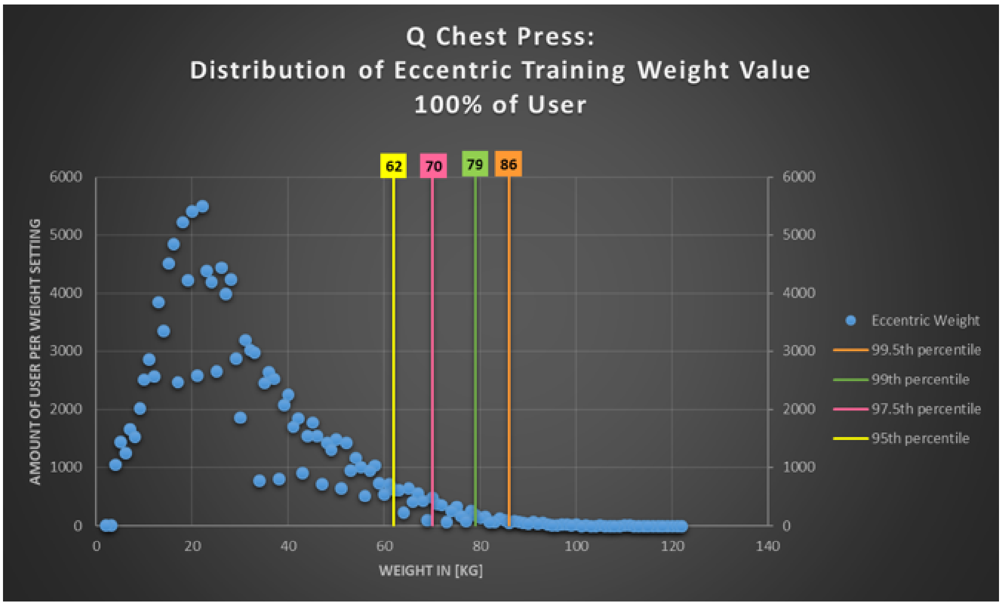


Figure 3.24: Eccentric training weight distribution Q Chest Press[25]

The concentric weight setting curve (M = 23.49 ± 12.76 kg, Mdn=19.00 kg) is like the eccentric weight setting curve (M = 29.42 ± 16.77 kg, Mdn=26.00 kg) right skewed. The user's actual training weight is compared to the user's individual maximum strength value obtained from the isokinetic maximum strength test. The percentage of the concentric training weight with respect to the user's individual maximum strength value is M = 40.80 ± 11.17 % and with respect to the eccentric training weight value it accounts for M = 50.75 ± 15.37 %.

Servo settings

The servo setting of the Q Chest Press is the adjustment for the height of the seating structure (see figure 3.25). The 0-setting is the bottom position and the 100-setting is the top position. The principle can be seen in figure 3.25.

[25]created with Microsoft Excel based on source: milon Care data extraction as of 5th March 2019

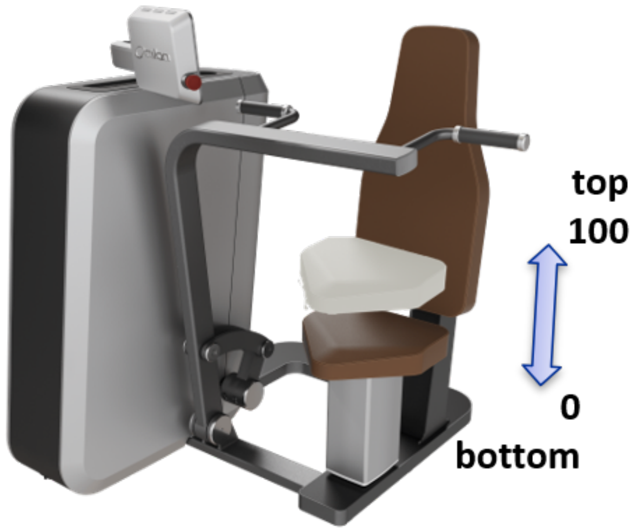


Figure 3.25: Servo-Setting illustration Q Chest Press: Seating height adjustment[26]

The distribution shows that the curve is shifted to the left from center (=50). There is an outlier at setting 19 being the default value (see figure 3.26). The top position (100-setting) is not utilized and the setting 85 is the maximum value adjusted by one user.

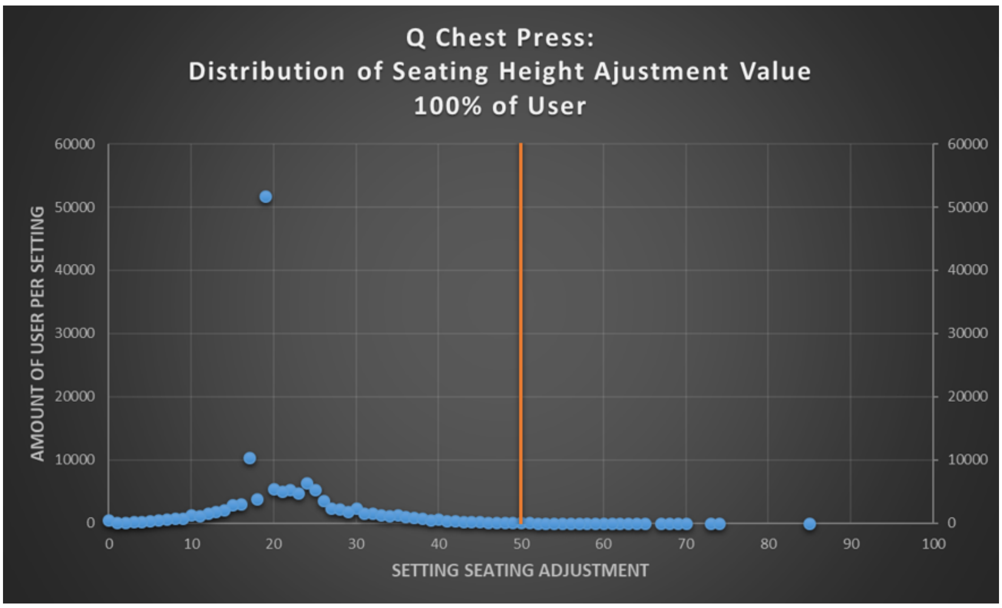
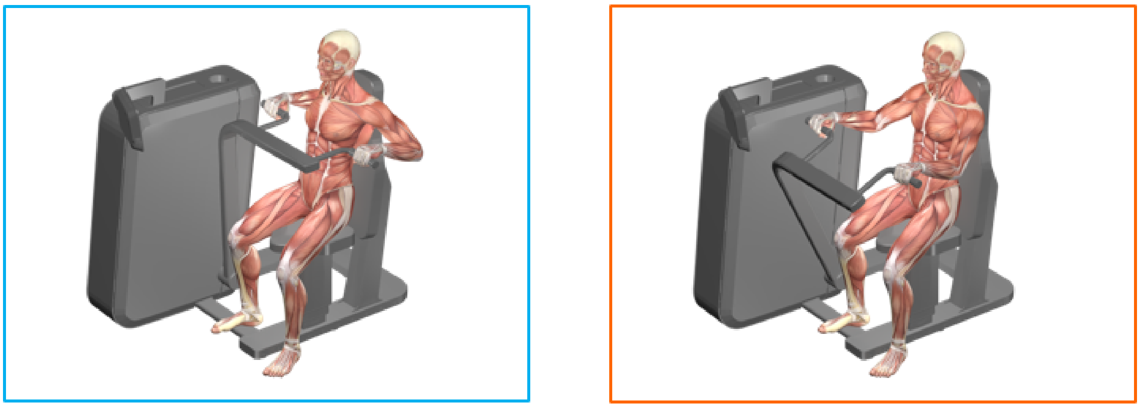


Figure 3.26: Lever arm adjustment distribution of Q Chest Press[27]

[26]edited figure retrieved from: R&D department milon industries GmbH, rendering with KeyShot by Luxion as of 21th December 2016
[27]created with Microsoft Excel based on source: milon Care data extraction as of 5th March 2019

ROM settings

The start position is with bend arms (figure 3.27a), whereby the end position is with straight arms (figure 3.27b).



(a) ROM start (b) ROM end

Figure 3.27: ROM illustration of Q Chest Press[28]

As can be obtained from the distribution of figure 3.28 the current range of ROM setting is fully utilized, but the most furthest position (= 100) is set by only 3 users. The outlier at settings 8 is a default value.

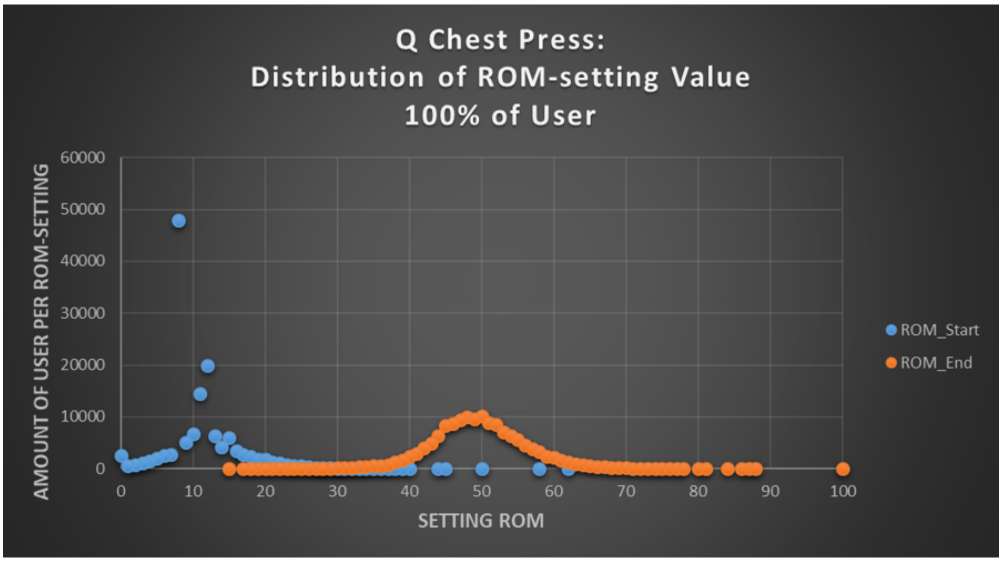


Figure 3.28: ROM distribution of Q Chest Press[29]

[28]edited figure retrieved from: R&D department milon industries GmbH, Software Poser as of 9th December 2016

[29]created with Microsoft Excel based on source: milon Care data extraction as of 5th March 2019

Conclusion

The maximum training load is neither reached in the maximum strength test nor in the actual training as concentric or eccentric weight by the users. Consequently a reduction of the maximum load can be considered.
The seating adjustment can be shifted towards the bottom position (0-setting) as the top position is not utilized.
The ROM setting can be considered to be decreased from the end position (100-setting) or shifted towards the 0-setting.

3.3.6. Data evaluation Q Seated Rowing

The machine Q Seated Rowing is used in a seated position with the user fixated by a chest support to counteract the rowing movement. The machine mainly targets the m.rhomboideus major and minor, but the m. latissimus dorsi, m. deltoideus pars spinalis and m. infraspinatus are also partly involved in the movement.
The raw data set consisted of 144875 line of data, i.e. amount of user. A total number of 140244 evaluable data sets remained after filtering the raw data sets relating to the requirements in chapter 3.3.1.

Maximum strength value

No user reach the machine's maximum load of 125 kg in the isokinetic strength measurement test. The maximum weight value reached by one user accounts for 124 kg (see figure 3.29). The curve is right skewed ($M = 48.48 \pm 19.99$ kg), which is confirmed by the median ($Mdn = 46.00$ kg) being smaller than the average value.

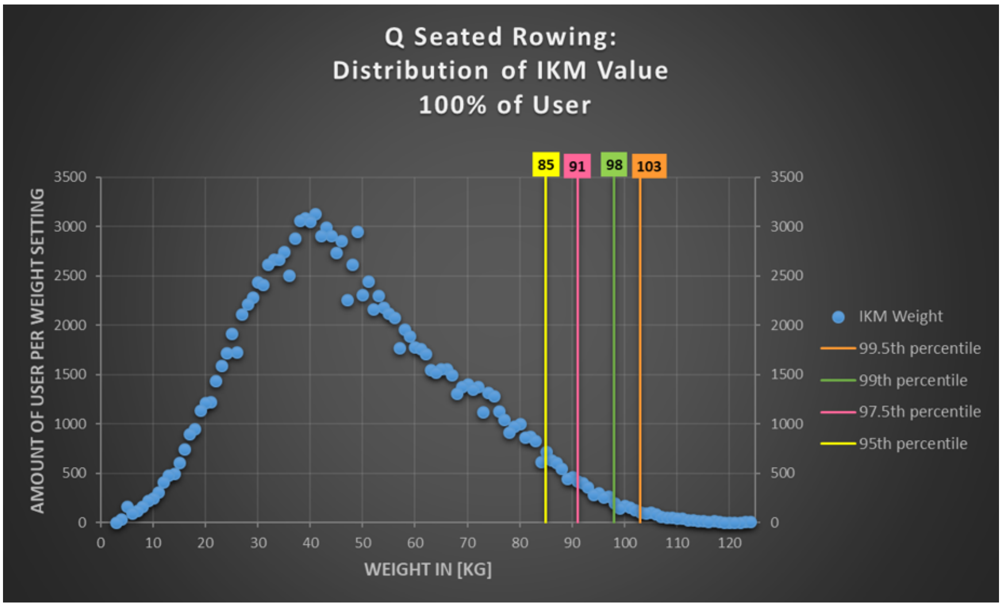


Figure 3.29: Maximum strength distribution Q Seated Rowing[30]

Concentric and Eccentric weight

Consequently no user actually trains with the maximum training weight setting of the machine for concentric or eccentric training weight (figure 3.30 and figure 3.31). The maximum value of 83 kg for concentric training weight is reached by one user.

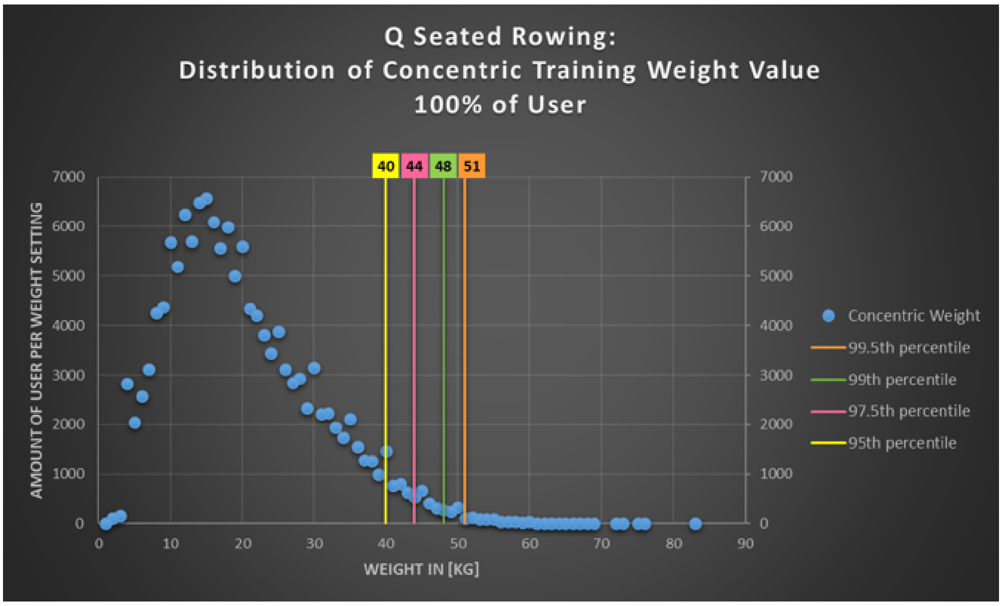


Figure 3.30: Concentric training weight distribution Q Seated Rowing[31]

[30]created with Microsoft Excel based on source: milon Care data extraction as of 5th March 2019

The maximum value of 107 kg for eccentric training weight is also reached by one user.

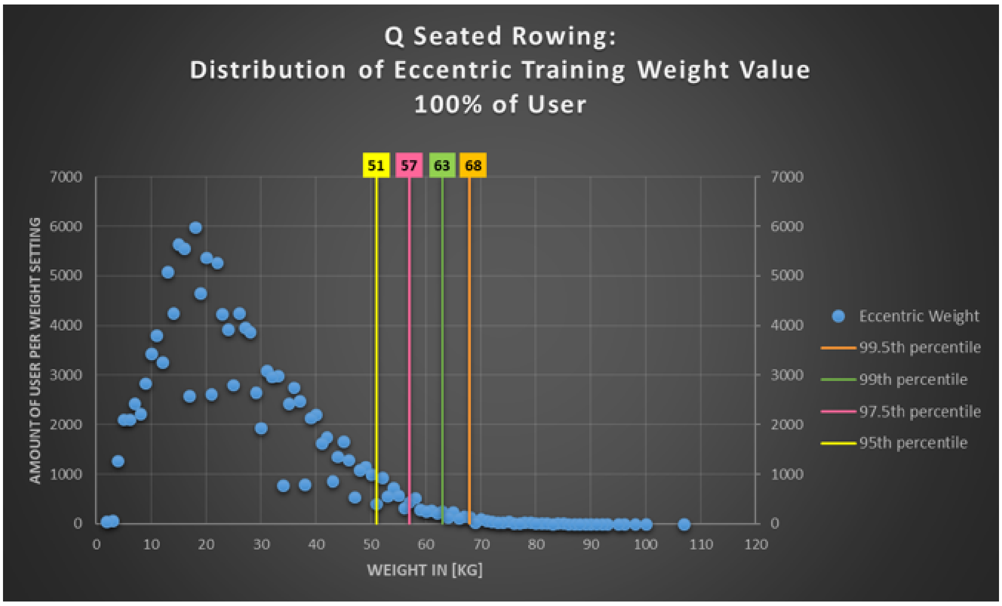


Figure 3.31: Eccentric training weight distribution Q Seated Rowing[32]

The concentric weight setting curve (M = 19.94 ± 10.23 kg, Mdn = 18.00 kg) is like the eccentric weight setting curve (M = 25.00 ± 13.48 kg, Mdn = 22.00 kg) right skewed. By comparing the user's actual training weight with the user's individual maximum strength value, the percentage of the concentric training weight with respect to the user's individual isokinetic maximum strength value accounts for M = 41.02 ± 11.93 % and for the eccentric training weight it is M = 51.04 ± 16.02 %.

Servo settings

The seating structure adjustment of the Q Seated Rowing is identical to the Q Chest Press (see figures 3.25 and 3.32). The 0-direction is the bottom position and the 100-direction is the top position.

[31] created with Microsoft Excel based on source: milon Care data extraction as of 5th March 2019
[32] created with Microsoft Excel based on source: milon Care data extraction as of 5th March 2019

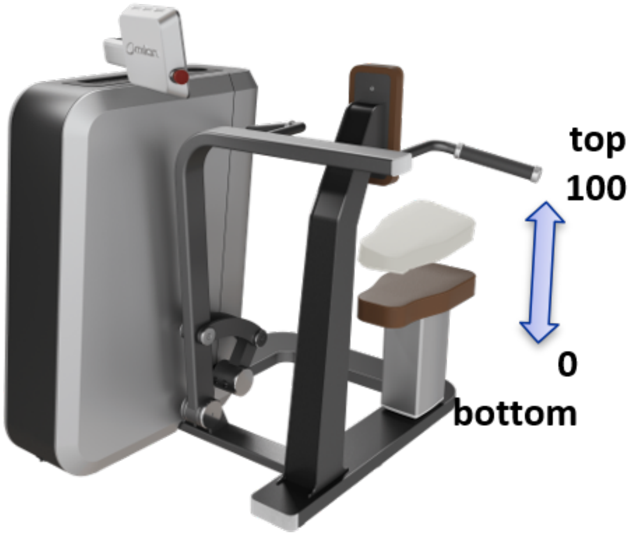


Figure 3.32: Servo-Setting illustration Q Seated Rowing: Seating height adjustment[33]

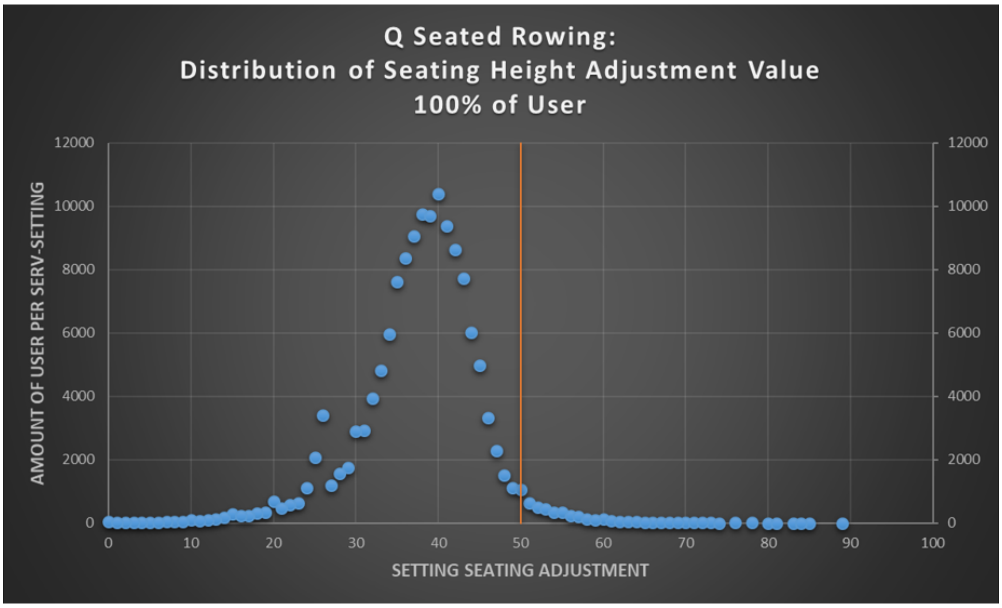


Figure 3.33: Lever arm adjustment distribution of Q Seated Rowing[34]

The distribution in figure 3.33 shows that the curve is shifted to the left from center (= 50). The top position (100-setting) is not used and the setting 89 is the maximum value adjusted by one user. Therefore the seating adjustment range could be decreased or shifted towards the 0-setting.

[33]edited figure retrieved from: R&D department milon industries GmbH, rendering with KeyShot by Luxion as of 21th December 2016

[34]created with Microsoft Excel based on source: milon Care data extraction as of 5th March 2019

ROM settings

(a) ROM start

(b) ROM end

Figure 3.34: ROM illustration of Q Seated Rowing[35]

The start position is with straight arms (figure 3.34), whereby the end position is with bend arms (figure 3.34).
As can be obtained from the distribution of figure 3.35 the current range of ROM setting is fully used. The outlier at settings 86 is a default value.

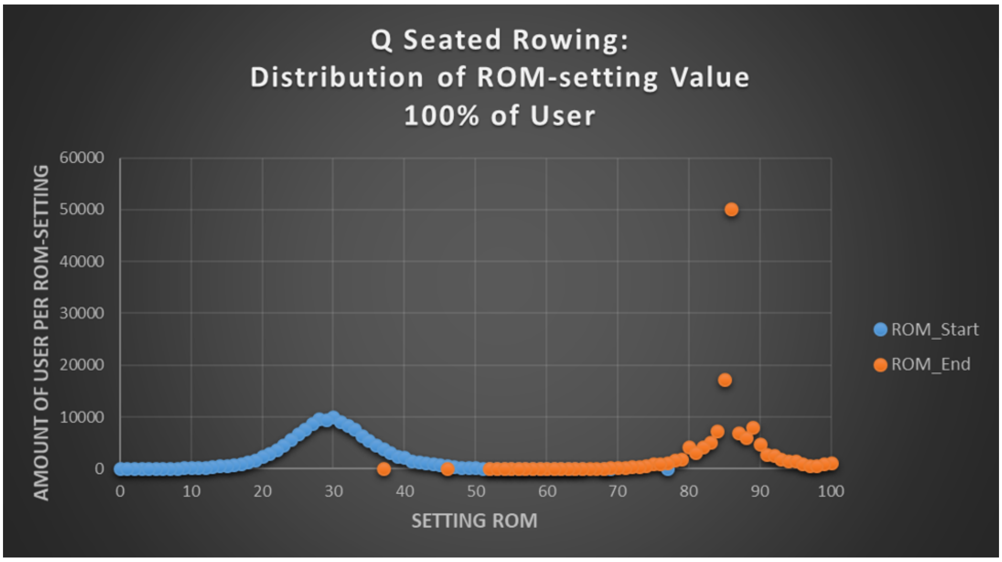


Figure 3.35: ROM distribution of Q Seated Rowing[36]

[35]edited figure retrieved from: R&D department milon industries GmbH, Software Poser as of 9th December 2016
[36]created with Microsoft Excel based on source: milon Care data extraction as of 5th March 2019

Conclusion

Similarly to the Q Chest Press the maximum training load is neither reached in the IKM nor in the actual training. Consequently a decrease of the machine's maximum load can be considered. The same thing goes for the seating adjustment, which should be decreased in adjustment range or shifted towards the bottom position (0-setting). For the ROM setting range there is no change necessary.

3.3.7. Data evaluation Q Abdominal Crunch

The Q Abdominal Crunch (see figure 3.36) is used in a seated position whereby the user is pushing a lever arm with straight hands away from him. The machine targets the m. rectus abdominis and the m. opliquus abdominis can also partly be involved in the movement.
The raw data set consisted of 148259 line of data, i.e. amount of user. After filtering relating to the requirements in chapter 3.3.1 a total number of 126683 evaluable data sets remained.

Figure 3.36: The training machine Q Abdominal Crunch[37]

[37] Rendering with KeyShot by Luxion, source: R&D department milon industries GmbH as of 21th December 2016

Maximum strength value

As can be obtained from figure 3.37 no user reaches the maximum weight of 100 kg. The maximum weight value reached by one user is 95 kg.

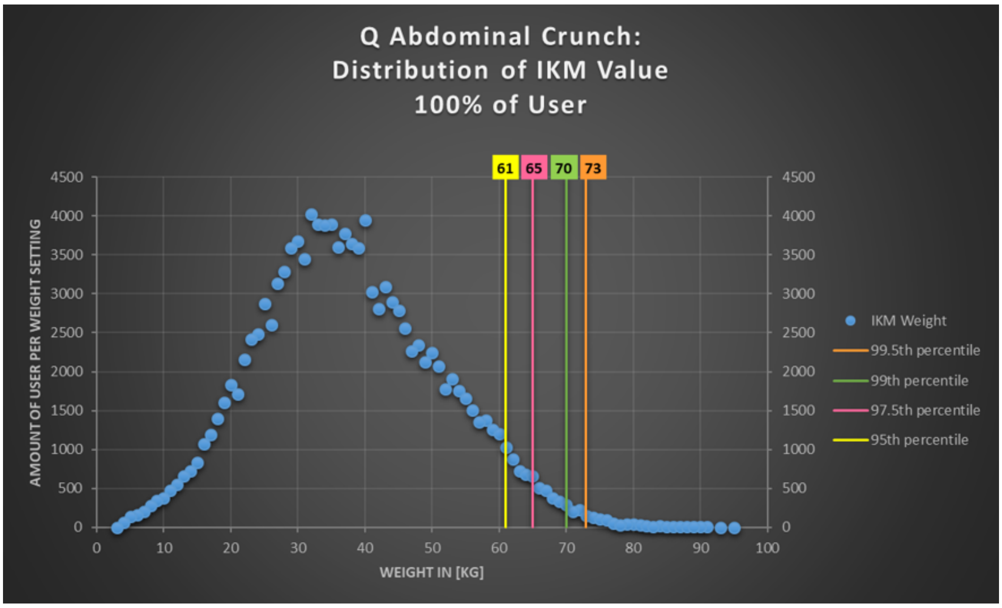


Figure 3.37: Maximum strength distribution Q Abdominal Crunch[38]

Concentric and Eccentric training weight

Consequently no user actually trains with the maximum training weight setting of the machine for concentric or eccentric training weight (figure 3.38 and figure 3.39). The maximum value of 62 kg for concentric training weight is reached by one user.

[38] created with Microsoft Excel based on source: milon Care data extraction as of 5th March 2019

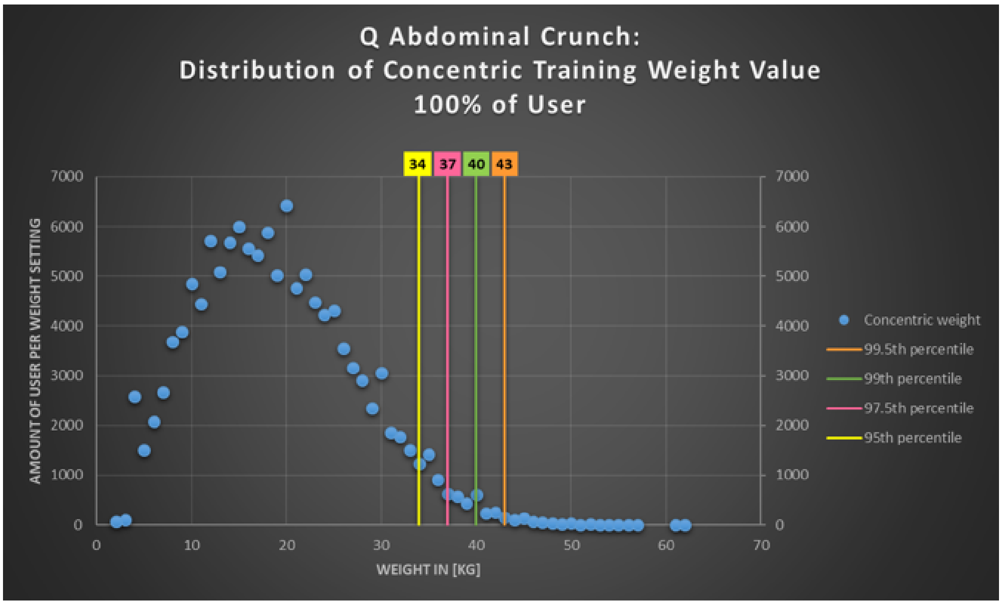


Figure 3.38: Concentric training weight distribution Q Abdominal Crunch[39]

The maximum value of 79 kg for eccentric training weight is also reached by one user.

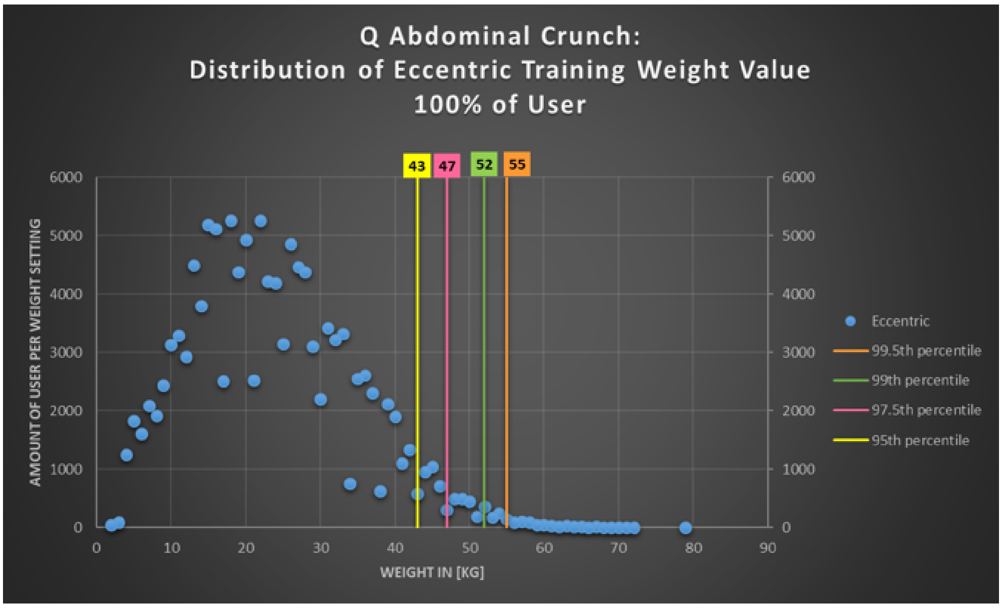


Figure 3.39: Eccentric training weight distribution Q Abdominal Crunch[40]

The concentric weight setting curve (M = 18.91 ± 8.39 kg, Mdn = 18.00 kg) is like the eccentric weight setting curve (M = 23.39 ± 10.95 kg, Mdn = 22.00 kg) right skewed.

[39]created with Microsoft Excel based on source: milon Care data extraction as of 5th March 2019
[40]created with Microsoft Excel based on source: milon Care data extraction as of 5th March 2019

The user's actual training weight is compared to the user's individual maximum strength value obtained from the isokinetic maximum strength test. The calculated percentage of the concentric training weight value with respect to the user's individual maximum strength value is $M = 50.22 \pm 14.05$ % and for the eccentric weight value it accounts for $M = 61.65 \pm 18.20$ %.

ROM setting

The ROM in start position is with straight arms (figure 3.40a). Initiating the movement without rounding the back, the end position does not alter the straight position of the arms (figure 3.40b).

(a) ROM start (b) ROM end

Figure 3.40: ROM of Q Abdominal Crunch[41]

The ROM settings show outlier at position 18 and 67 (see figure 3.41). Those describe the default values, i.e. not altered values after measurement with the milonizer.

[41]edited figure retrieved from: R&D department milon industries GmbH, Software Poser as of 9th December 2016

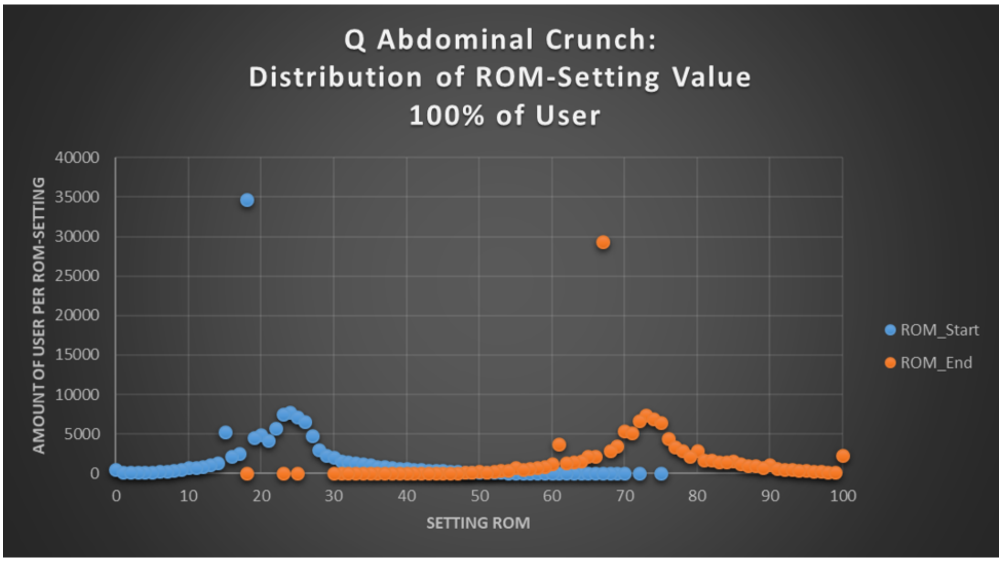


Figure 3.41: ROM distribution of Q Abdominal Crunch[42]

Conclusion

Neither is the maximum training load reached in the IKM nor in the actual training as concentric or eccentric weight by the user. Therefore a decrease of the machine's maximum load can be considered.

3.3.8. Data evaluation Q Back Extension

The Q Back Extension is being used in a seated position and the machine targets the m. erector spinae.
The raw data set consisted of 146583 line of data, i.e. amount of user. After filtering the raw data set relating to the requirements in chapter 3.3.1 a total number of 132072 evaluable data sets remained.

Maximum strength value

A total number of 2250 user reach the maximum load of the machine. It is to note that the machine is limited to 100 kg and a potential maximum strength value of over 100 kg is not recorded even if the user would be able to exceed this limit (see chapter 3.3.4, Maximum strength value, p. 36). The IKM curve is right skewed as the average value is M = 53.00 ± 19.07 kg and the median accounts for Mdn = 51.00 kg (see figure 3.42).

[42]created with Microsoft Excel based on source: milon Care data extraction as of 5th March 2019

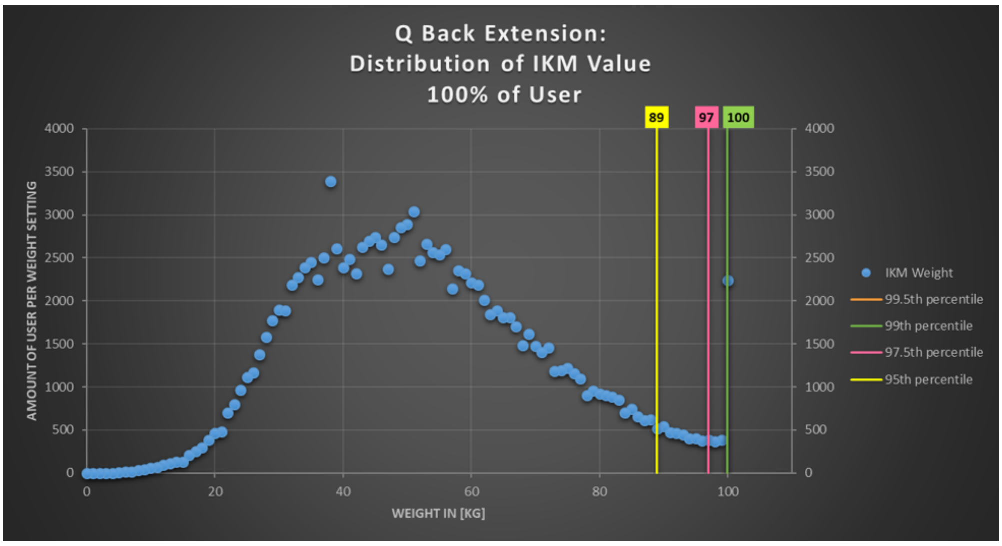


Figure 3.42: Maximum strength distribution Q Back Extension[43]

Concentric and Eccentric weight

Two users train with the maximum load setting as the concentric training weight (see figure 3.43).

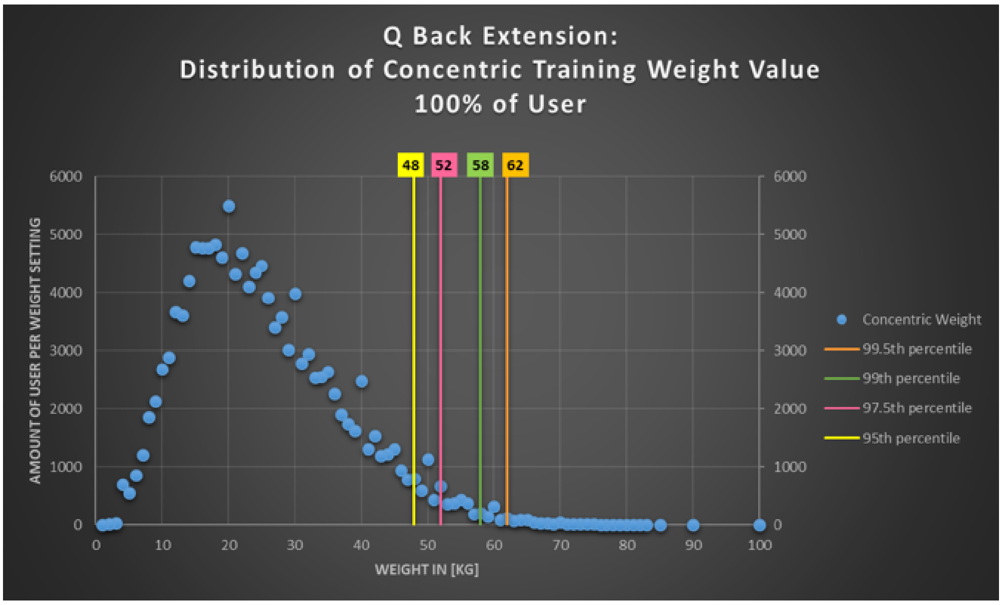


Figure 3.43: Concentric training weight distribution Q Back Extension[44]

[43]created with Microsoft Excel based on source: milon Care data extraction as of 5th March 2019
[44]created with Microsoft Excel based on source: milon Care data extraction as of 5th March 2019

Nine users train with the maximum load setting as eccentric training weight (see figure 3.44).

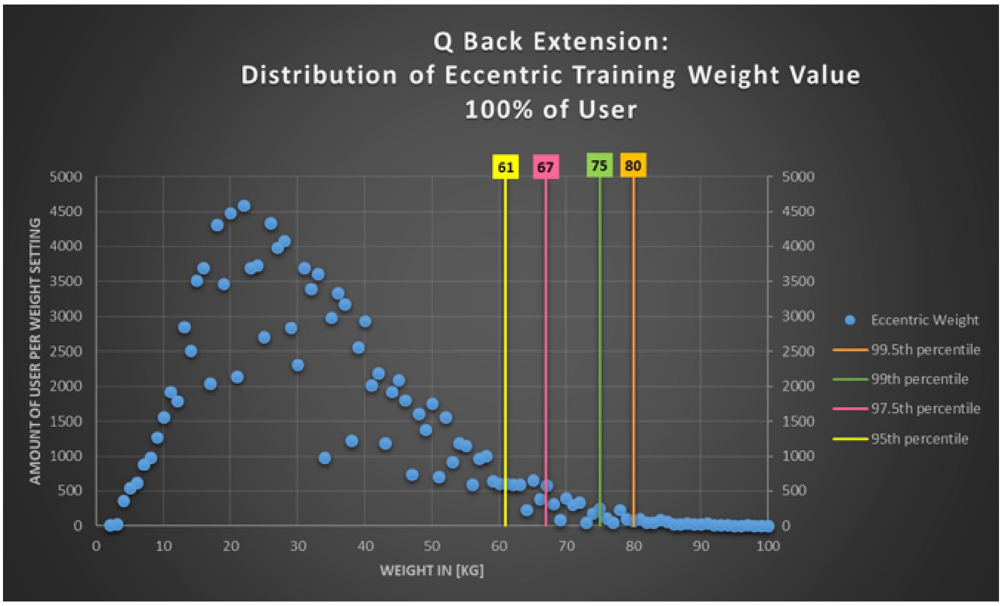


Figure 3.44: Eccentric training weight distribution Q Back Extension[45]

The comparison of actual training weight with maximum strength weight show that the training weight curves are right-skewed distributed. The concentric weight setting curve (M = 25.25 ± 11.88 kg, Mdn = 23.00 kg) thereby show a similar distribution form as the eccentric weight setting curve (M = 31.37 ± 15.52 kg, Mdn = 28.00 kg). By comparing the user's actual training weight with the user's individual maximum strength value obtained from the isokinetic maximum strength test, the percentage of the concentric training weight value with respect to the user's individual maximum strength value accounts for M = 47.21 ± 13.10 % and for eccentric training weight value it is M = 58.29 ± 17.33 %.

Servo settings

The adjustment for the lever arm position is possible for this machine and the principle can be seen in figure 3.45.

[45]created with Microsoft Excel based on source: milon Care data extraction as of 5th March 2019

Figure 3.45: Servo-Setting illustration Q Back Extension[46]

The distribution of the curve shows that the full range is used (figure 3.46). There is an outlier at setting 65 (6407 user, 4.85 % of 132072 users), which is the default value. It can furthermore be observed that there is an outlier at setting 0, as well as at setting 100, meaning that the whole lever arm adjustment range should be expanded for the Q series.

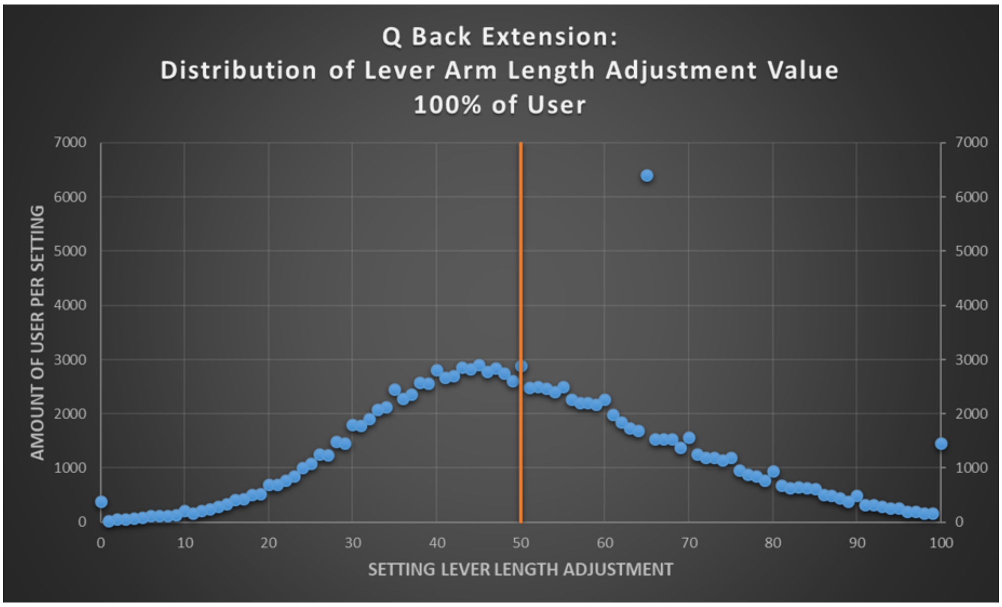
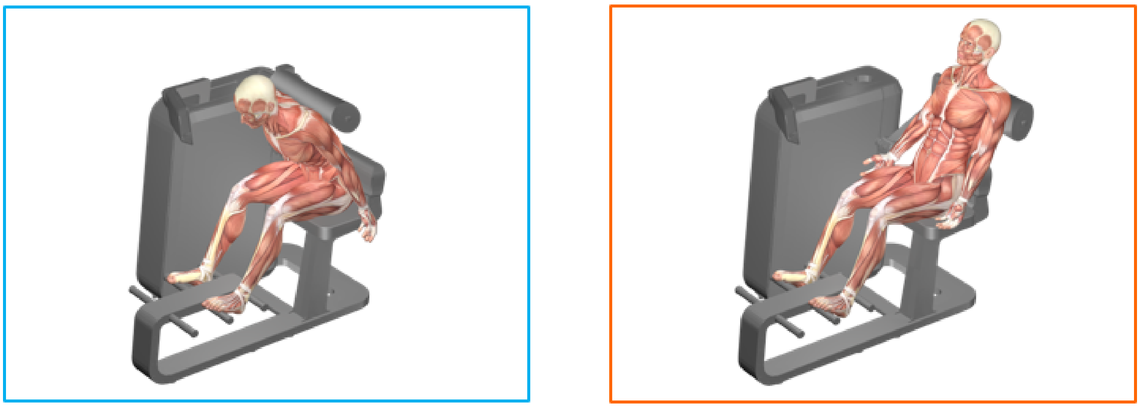


Figure 3.46: Lever arm adjustment distribution of Q Back Extension[47]

[46]edited figure retrieved from: R&D department milon industries GmbH, rendering with KeyShot by Luxion as of 21th December 2016

ROM settings

The start position is with bent hips (see figure 3.47a). Initiating the movement without rounding the back, the end position is with extended hips (see figure 3.47b).



(a) ROM start (b) ROM end

Figure 3.47: ROM of Q Back Extension[48]

As can be obtained from the distribution of figure 3.48 the current range of ROM setting is sufficient for a physiological training position.

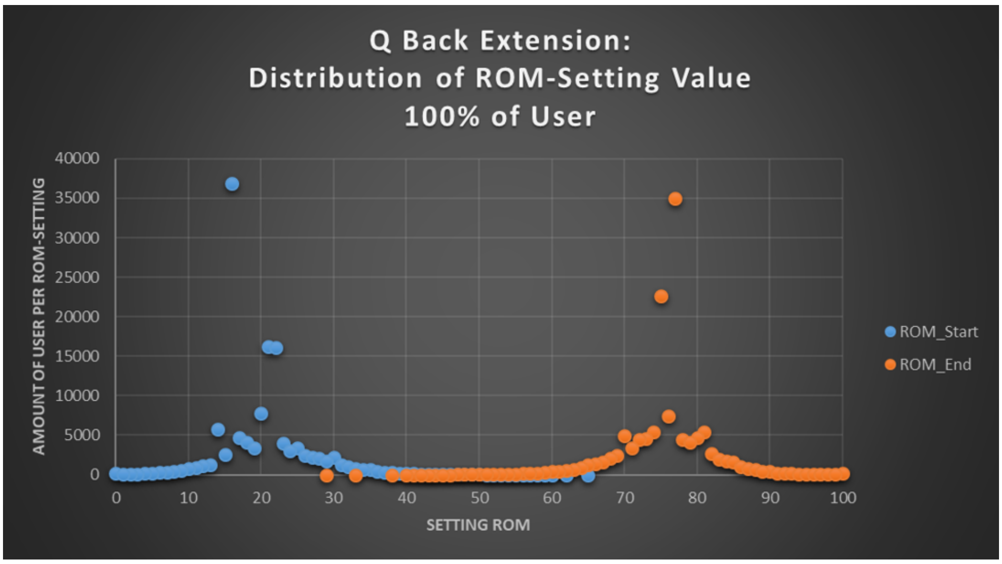


Figure 3.48: ROM distribution of Q Back Extension[49]

[47]created with Microsoft Excel based on source: milon Care data extraction as of 5th March 2019

[48]edited figure retrieved from: R&D department milon industries GmbH, Software Poser as of 9th December 2016

[49]created with Microsoft Excel based on source: milon Care data extraction as of 5th March 2019

Conclusion

An increase of maximum load of the machine can be considered if the isokinetic parameters of the IKM remains unchanged (see chapter 3.2.2). The lever arm adjustment can be constructed longer. For the ROM setting adjustment there is no change necessary.

3.3.9. Findings of data analysis

All findings and conclusions are summed up in table 3.2 below

Strength machine	Conclusion for data analysis
Q Leg Curl	IKM sufficient expand adjustment range of back support or shift it towards 0-setting lever arm length adjustment should be expanded towards the 0-setting ROM setting could be expanded in the end range
Q Leg Extension	IKM not sufficient expand adjustment range of back support or shift it towards 0-setting lever arm length adjustment should be expanded in the shorter position
Q Chest Press	IKM more than sufficient seating height adjustment adjustment range should be decreased or be shifted towards 0-settings
Q Seated Rowing	IKM more than sufficient seating height adjustment adjustment range should be decreased or be shifted towards 0-settings
Q Abdominal Crunch	IKM more than sufficient
Q Back Extension	IKM not sufficient lever arm length adjustment should be expanded for the whole range

Table 3.2: Summary of the conclusions from the data analysis

Conclusions drawn from the findings of the data analysis have to be differentiated with respect to the current and the cost reduced series. For instance the cost reduced series can have a lower maximum load or a narrower adjustment range to distinguish from the current series. The conclusions drawn for both series are summed up below.

Conclusions for the current Q series

1. For the machines Q Leg Extension and Q Back Extension an increase of maximum load can be considered to satisfy the needs of all users. That is in the case of not changing the current isokinetic parameters of the maximum strength test.

2. The evaluation of the seating and lever arm length adjustment show different issues. For the machines Q Chest Press and Q Seated Rowing the left shift of the curves (see figure 3.26 and figure 3.33) and the non usage of the top settings indicate that the current seating adjustment is defined to broad.

3. For the machine Q Leg Curl the back support adjustment curve (see figure 3.8) shows that an extension of the adjustment range is necessary.

4. The machine Q Leg Extension needs an expansion of the back support adjustment in 0-setting to fit user with longer thighs (see figure 3.17). Due to the common parts principle the whole adjustment range of the two machines should be extended.

5. The lever arm length adjustment for Q Leg Curl and Q Leg Extension (see figure 3.10 and figure 3.19) should be shorter. While the lever arm length adjustment for the Q Back Extension (see figure 3.46) should be longer. In conclusion the whole adjustment range of the lever arm should be extended as all three machines inherits this component group.

3.3.10. Conclusion for the cost reduced series

1. Upon evaluating the data from milon Care it can be concluded that few user reach the maximum load value (except for the machines Q Leg Extension and Q Back Extension) in the IKM. Consequently few user if any trains with the maximum load.

2. With the concept of a cost reduced series in mind it should be considered if there is a possibility to reduce the machines maximum load. In that way a less powered motor unit can be used. For the machines Q Chest Press and Q Seated Rowing a direct flange mount connection between lever arm and motor could be considered. Therefore it should be determined for each machine what training load is sufficient to at least satisfy the 95th percentile of all users.

3. The current parameters of the IKM should be reviewed upon an alternative for training load determination leading to a decrease in maximum load.

4. According to DIN 33402-2 Bbl 1:2006-08 the 5th and 95th percentiles are normally used as limits when constructing for work equipment and workplace. This should be considered when developing alternative concepts regarding the adjustment range (servo and ROM settings).

3.4. Function cost analysis

To determine which components should be evaluated in detail a cost structure is developed. This method highlights the components the focus should be on when developing alternative concepts. It is a tool for identifying the highest costs and thus should guide the developer into focusing on the right issues and prevent him to get lost into detail for component groups, which have little cost reducing impact [16, pp. 623-625].

For this case cost structures for component groups and product functions should be considered. Single component costs and functions are assigned to component groups with the aim to identify potential cost drivers.

Due to the companies regimes for handling sensitive data the absolute costs in € will not be published[50]. In order to display cost differences of component groups between the machines a new unity - the milon coin (MC) - is hereby defined, which will be further referred to as MC. The factor is randomly defined as 50000 MC being the total material cost in € for the Q Leg Curl.

3.4.1. Cost analysis of generic component groups

The first step is the definition of generic component groups valid for all strength machines.

Component groups	**Description**
Power unit	Electrical motor, incremental encoder
Casing optics	Visible parts including C-profile sheet metal, end caps
Human machine interface	Display unit including connection site, pulse receiver
Lever arm	Including grips, auxiliary drive
Mechanical limiter, load transfer	Shaft, stop plate, limiter
Cushion	Seating, back support, lever arm cushions
Frame Construction	Including foot stand, load attachment plate
Control cabinet	Including electrical components
Side mounting	Including foot rest, inserts
Seat structure	Including support structures, auxiliary drives
Electrical periphery	Cables, plug connectors,...
Mechanical periphery	Screws, washers,...

Table 3.3: Definition of component groups

The single component costs are assigned to the corresponding component groups. Figure 3.49 shows exemplary which percentage share the component group have on the whole machine.

[50] personal interview with the Chief Financial Officer (CFO) as of 27th May 2019

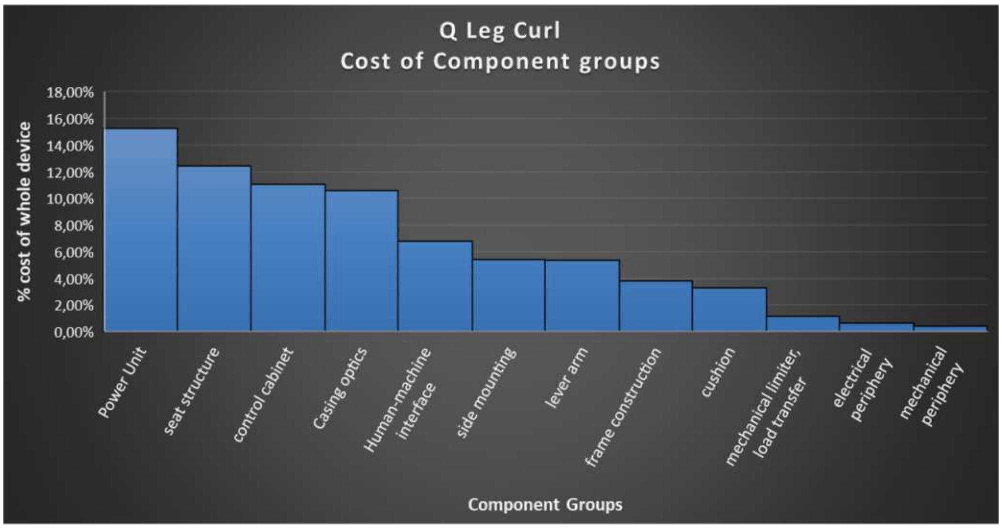


Figure 3.49: Component group cost Q Leg Curl[51]

Due to the fact that the machines vary widely the cost distribution is different for every machine type. The analysis for the other machines of batch 1 can be found in the appendix (see chapter A.2).

3.4.2. Function analysis

A function analysis is used to define certain functions a product has to fulfil. It is helpful to determine the purpose of the product before thinking about concrete measures in changing or removing components [15, p. 55].
The functions affecting the strength training machines as well as its interaction with the user are formulated in table 3.4.

[51]created with Microsoft Excel based on rating with the head and deputy head of R&D department as of 24th April 2019

Functions	Description
Providing training resistance	Resistance for user training
Ensuring user security	Protect user health from potential harm
Electronic control	Control drive units
Ensuring usability	E.g. easy access to machine, display handling
Ensuring user's physiological training position	E.g. ROM, seating position, grip position
Structural safety of machine	Overall structure safety of machine against deforming, turning over
Assistance structures for user	E.g. Down holder for legs, grip structures on seating structures
Exercise feedback	Information about user's training (e.g. repetitions, load, training speed)
Aesthetic product design	Outer shape, visually perceivable parts

Table 3.4: Definition of component groups

3.4.3. Pairwise comparison of functions

The method of pairwise comparison is a tool to compare two features directly with each other upon which is better. The valuation is graded with 1 for "better than..." and 0 for "worse than...". Thus it produces a order of priority for those features [16, pp. 514-515]. Since the defined functions are of a qualitative rather than a quantitative nature this method is applied for this issue. In addition the rating is expanded, because in some cases two functions could be seen as equally important. The valuation is therefore graded with 2 for "more important than...", with 1 for "equivalent to..." and 0 for ""less important than...",

Figure 3.50 shows the weighted functions after rating with the head and the deputy head of mechanical development department.

more \ than	Providing trainings resistance	Ensuring User security	Electronic control	Ensuring usability	Ensuring user's physiological training position	Structural safety of machine	Assistance for User	Excercise feedback	Aesthetic product design	sum	%
Providing trainings resistance		0	1	1	1	0	2	2	2	9	12,50%
Ensuring User security	2		2	2	2	2	2	2	2	16	22,22%
Electronic control	1	0		0	1	0	1	2	2	7	9,72%
Ensuring usability	1	0	2		1	0	1	2	2	9	12,50%
Ensuring user's physiological training position	1	0	1	1		0	2	2	2	9	12,50%
Structural safety of machine	2	0	2	2	2		2	2	2	14	19,44%
Assistance for User	0	0	1	1	0	0		2	1	5	6,94%
Excercise feedback	0	0	0	0	0	0	0		1	1	1,39%
Aesthetic product design	0	0	0	0	0	0	1	1		2	2,78%

Legend		
2	1	0
More important	Equivalent	less important

Figure 3.50: Pairwise comparison of function[52]

[52]created with Microsoft Excel based on rating with the head and deputy head of R&D department as of 24th April 2019

Providing training resistance is the crucial factor for using the machine, but nevertheless it is rated less important than the safety aspects. The reason is that a working machine harming the user or itself can not be considered as functional.
The aspects electronic control, ensuring usability and the users' physiological training position are seen as equivalent as the functions are interconnected. Less important are the aspects assistance for user, exercise feedback and aesthetic product design with respect to the training resistance.
The security aspect for the user and the machine itself is rated as most important, whereby the ensuring the users' security is the most important function.
Ensuring users' physiological training position is seen as equivalent to usability and the two functions consequently have the same summed up rating.
The function electronic control can be seen as equivalent with assistance for user, but has a higher summed up rating as it is also responsible for adjusting training resistance and ensuring users' physiological training position.
At the other end of the spectrum the aesthetic product design is rated the least important function and is equivalent to assistance for user and exercise feedback. Exercise feedback is seen as even less important.
Overall it can be stated, that the security for the user and the machine is the number one priority. Providing training, ensuring users' physiological training position and the usability is crucial for proper functioning of the machine. Consequently it is the runner up behind the security aspect.

3.4.4. Function assignment with component groups

The next step is to assign the functions to the different generic component groups.

	Q Leg Curl	Function groups								
		Providing trainings resistance	Ensuring User security	Electronic control	Ensuring usability	Ensuring user's physiological training position	Structural safety of machine	Assistance for User	Excercise feedback	Aesthetic product design
Component Groups	Power Unit	2	0	0	0	0	0	0	1	0
	Casing optics	0	1	0	0	0	0	0	0	2
	Human-machine-interface	0	0	2	2	1	0	0	2	2
	lever arm	2	0	0	1	2	0	0	0	1
	mechanical limiter, load transfer	2	2	0	0	0	0	0	0	0
	cushion	0	1	0	1	1	0	0	0	2
	frame	0	0	0	0	0	2	0	0	1
	control cabinet	1	0	2	0	1	0	0	1	0
	side mounting	0	0	0	0	0	2	0	0	1
	seat structure	0	0	0	1	2	1	1	0	1
	electrical periphery	0	0	1	0	0	0	0	0	0
	mechanical periphery	0	0	0	0	0	1	0	0	0

Legend		
2	1	0
main function	secondary funciton	no function

Figure 3.51: Assignment of function to component groups for Q Leg Curl[53]

The rating will be explained in detail below. A rating of 2 is given if the component group fully meet the function. If it is a secondary function it gets rated with a 1 and if it does not fulfil the function it gets a rating of 0.

The function assignment is explained on the example of the Q Leg Curl (see figure 3.51). The other machines follow a similar rating, except for a few variations in several component groups, which are marked yellow in figure 3.51.

The power units' main function is to provide resistance and provide the user with a feedback through different loading.

The casing of the machine is mainly responsible for aesthetics. It also prevents the user to get in contact with movable parts.

The human machine interface, mainly consisting of the display unit, fulfils the function of being a part of the operating element for the electronic control and therefore is also responsible for setting the users' physiological training position. It ensures the usability for the user by reacting upon tactile stimulation and giving visual training feedback. In case of aesthetic product design it plays a crucial role being a visible part usually not common for training machines.

The lever arm is the connection transferring the resistance from the power unit to the user. It provides the user with an easy handling through proper positioning and ensures

[53]created with Microsoft Excel as of 24th April 2019

a physiological training position by length adjustment. For the Abdominal Crunch, Chest Press and Seated Rowing a 1 will be substituted, because the grip position ensures a proper training position. A secondary function is aesthetics, because it is visible component.
The mechanical limiter is crucial for the users' security in case of a malfunction. The load transfer is the connection between motor and lever arm.
The cushion is a visible component. It provides usability by a comfortable feeling, e.g. pain free movement when comparing with pressing against a steel rod. Therefore it is also responsible for the users' physiological position. For the Leg Curl, Leg Extension and Back Extension the valuation for ""ensuring users security" is 1. Without the cushion the movable lever arm could harm the user as it is in direct contact with the Achilles tendon, shinbone or thoracic spine. For the other machines the rating is 0.
The frames function is to provide structural safety for the machine. Because it inherits most of the components, its shape has also an influence on aesthetic product design.
The control cabinets function is the electronic control. It is also necessary for regulation of optimal training load and setting of training position.
The side mounting acts as counter bearing for the machine and is also a visible part. For the machines Abdominal Crunch and Back Extension the foot rest helps the user to get into the proper training position. The yellow marked boxes is rated in that case with 1. The valuation for the other machines is 0.
The seat structure is a visible part and mainly responsible for a proper training position and assist the user with an easy access to the machine. In Case of the Leg Curl and Leg Extension additional grips support the user with his exercise. In that case the rating is 1. For the other machines the rating is 0.

3.4.5. Function cost matrix

To collect and manage all the information a function cost matrix is created to display cost drivers for both functions and component groups.
Exemplary the function cost matrix of the Q Leg Curl is displayed in figure 3.52. The matrices for the other strength machines are calculated in the same way and can be found in the appendix (see chapter A.3). The calculated target costs are abstract numbers derived from the paired function analysis (see figure 3.50) and the allocation of functions to component groups (see figure 3.51). This tool should display component groups which are cost drivers and can be examined further in detail.

Component Groups / Q Leg Curl	Providing trainings resistance	Ensuring User security	Electronic control	Ensuring usability	Ensuring user's physiological training position	Structural safety of machine	Assistance for User	Excercise feedback	Aesthetic product design	sum function of component group	atual component group costs [MC]	actual % of component group costs	target component cost from paired comparison [MC]	target % of component cost from paired comparison	delta target-actual cost [MC]	delta target-actual in %
Power Unit	2	0	0	0	0	0	0	1	0	3	7637,89	15,28%	3061,22	6,12%	-4576,66	-59,92%
Casing optics	0	1	0	0	0	0	0	0	2	3	4499,62	9,00%	3061,22	6,12%	-1438,40	-31,97%
Human-machine-interface	0	0	2	2	1	0	0	2	2	9	5964,60	11,93%	9183,67	18,37%	3219,07	53,97%
lever arm	2	0	0	1	2	0	0	0	1	6	4415,19	8,83%	6122,45	12,24%	1707,26	38,67%
mechanical limiter, load transfer	2	2	0	0	0	0	0	0	0	4	899,72	1,80%	4081,63	8,16%	3181,91	353,65%
cushion	0	1	0	1	1	0	0	0	2	5	2510,19	5,02%	5102,04	10,20%	2591,85	103,25%
frame	0	0	0	0	0	2	0	0	1	3	2803,91	5,61%	3061,22	6,12%	257,32	9,18%
control cabinet	1	0	2	0	1	0	0	1	0	5	7800,06	15,60%	5102,04	10,20%	-2698,02	-34,59%
side mounting	0	0	0	0	0	2	0	0	1	3	3814,15	7,63%	3061,22	6,12%	-752,92	-19,74%
seat structure	0	0	0	1	2	1	1	0	1	6	8838,46	17,68%	6122,45	12,24%	-2716,01	-30,73%
electrical periphery	0	0	1	0	0	0	0	0	0	1	498,89	1,00%	1020,41	2,04%	521,52	104,54%
mechanical periphery	0	0	0	0	0	1	0	0	0	1	317,33	0,63%	1020,41	2,04%	703,07	221,56%
sum of function	7	4	5	5	7	6	1	4	10							
actual function costs [MC]	7142,86	4081,63	5102,04	5102,04	7142,86	6122,45	1020,41	4081,63	10204,08							
actual % of function cost	14,29%	8,16%	10,20%	10,20%	14,29%	12,24%	2,04%	8,16%	20,41%							
sum of weighted function	16	20	11	14	16	20	5	7	12							
% of weighted function	13,22%	16,53%	9,09%	11,57%	13,22%	16,53%	4,13%	5,79%	9,92%							
target function cost from paired comparison [MC]	6611,57	8264,46	4545,45	5785,12	6611,57	8264,46	2066,12	2892,56	4958,68							
delta target-actual cost [MC]	-531,29	4182,83	-556,59	683,08	-531,29	2142,01	1045,71	-1189,07	-5245,40							
delta target-actual in %	-7,44%	102,48%	-10,91%	13,39%	-7,44%	34,99%	102,48%	-29,13%	-51,40%							

Legend		
2	1	0
main function	secondary funciton	no function

Figure 3.52: Function cost matrix for Q Leg Curl[54]

[54]created with Microsoft Excel as of 24th April 2019

The values from the function to component groups assignment in chapter 3.4.4 can be summed up vertically or horizontally.
A look on the functions is taken by vertically summing up the values. Their individual percentage share upon all functions is calculated (*"% of function"*). Multiplying the individual percentages with the total material cost of the machine gives the value for the actual function cost (*"actual function costs [MC]"*). The next step is taking the weighted functions from the pairwise comparison (see chapter 3.4.3) into account by summing up the values (*"sum of weighted functions"*). Calculating that individual percentage share and multiplying it with the material cost of the component groups gives the target function cost (*"target function cost from pairwise comparison [MC]"*). The last step is to evaluate which functions are too expensive, i.e. where the actual function cost exceed the target function cost (*"delta target-actual cost"*). Those functions are marked red in the matrix.
A look at the component groups is taken, by horizontally summing up the values. The summed up values are in this case the target component cost after taking their percentage share and multiplying it with the total material cost of the machine (*"target component group cost from pairwise comparison [MC]"*). The actual component cost (*"actual component group costs [MC]"*) can be obtained from the cost determination of generic component groups (see chapter 3.4.1). Similarly to the function costs the target and actual component group cost are evaluated in that way (*"delta target-actual component group cost [MC]"*). If the actual cost exceed the target cost the component group is marked red in the matrix.

Cost of Functions

The comparison of actual and target function cost is visualized in figure 3.53 exemplary for the Q Leg Curl.

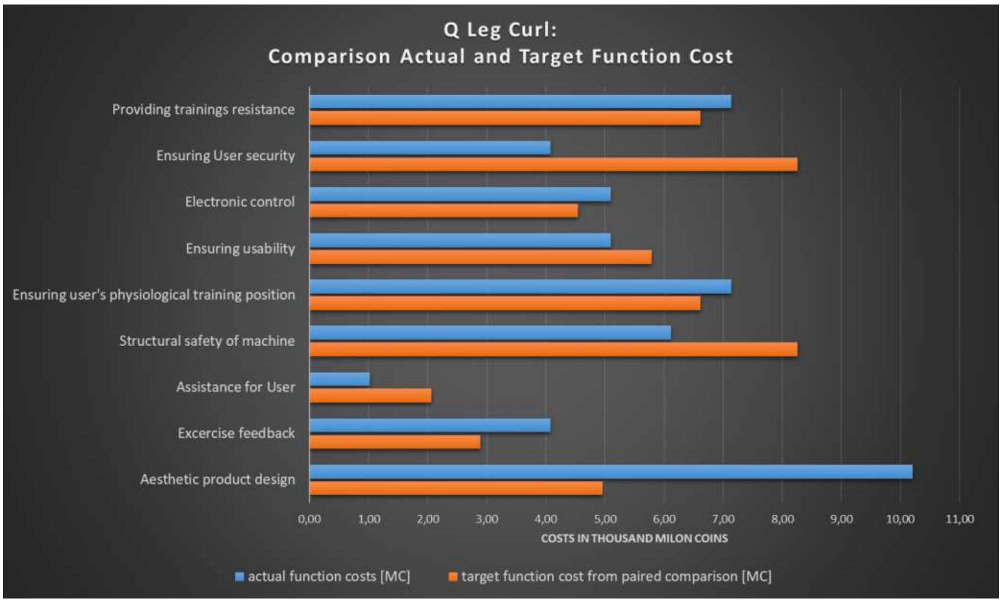


Figure 3.53: Comparison of current and target function cost for Q Leg Curl[55]

Following functions can be considered as too expensive:

- Providing training resistance
- Electronic control
- Ensuring users' physiological training position
- Exercise feedback
- Aesthetic product design

The comparison of actual and target cost for the other strength training machines show similar results (see chapter A.4). The differences can be lead back to varying component group cost for every machine. For instance the seat structure is not adjustable for every machine and the cost for the auxiliary drive therefore not included.

[55]created with Microsoft Excel as of 20th May 2019

Cost of Component Groups

Figure 3.54 shows the comparison of actual and target function cost exemplary for the Q Leg Curl.

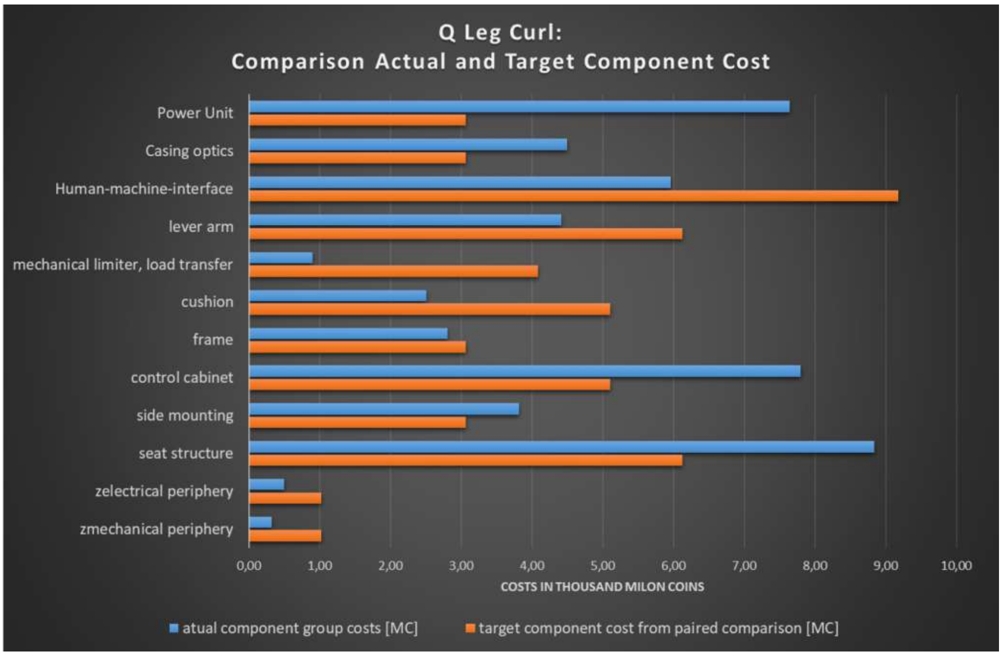


Figure 3.54: Comparison of current and target component group cost for Q Leg Curl[56]

Following component groups can be considered as too expensive:

- Power unit
- Casing optics
- Control cabinet
- Side mounting
- Seat structure

The analyses for the other machines are similar and can be obtained in the appendix (see chapter A.4).
With those findings a detailed investigation into the respective functions and component groups are made.

[56]created with Microsoft Excel as of 20th May 2019

3.5. Technical concepts for alternative component groups

Before developing concepts the findings from the Data analysis (see chapter 3.3.9) and function cost analysis (see chapter 3.4.5) are worked up and presented in a workshop with the mechanical department as of 24th April 2019. Existing suggestions were assessed and new ideas developed through the tool of brain storming.

3.5.1. Result from the R&D Workshop

The result of the workshop can be summarized in several points. The function and component groups with the greatest potential will be analysed in detail.

- For aesthetic product design a look on all visible components individually should be conducted.
- No architecture change of the frame construction should be considered as it is the one component all machines have in common. A change of shape would generate more costs, instead of generating synergy effects (see chapter 4.4).
- Consequently the shape of the casing should stay the same due to satisfying a modular construction. A shape change of the casing would lead to a shape change of the frame construction. Furthermore, the existing moulding dies cannot be used for the new series and new moulding dies have to be produced.
- An alteration of the control cabinet should not be considered as the shape fits right into the frame construction and the electronic parts inside are already compatible with each other.
- A change of architecture for the seat structure and side mounting should be considered.
- A change of a less powered motor unit is just feasible for the machines with upper pivot point (Leg Curl, Leg Extension and Back Extension).
- A further investigation into seating position adjustment without auxiliary drive should be done. Concepts for mechanical adjustments should be investigated.

Further a modular construction is desired as well as using as many common parts as possible. It should be striven to generate synergy effects, i.e. reducing the material costs for the current and the new product series in the long term by purchasing of specific components in higher batch sizes.

Overview

Table 3.5 provides an overview of the developed concepts and the chapters, in which they are explained in detail. Before developing concepts several points regarding the findings of the data analysis should be considered. According to DIN 33402-2 Bbl 1:2006-08 the usual procedure for constructing work equipment and work place for the user is taking the 5th and 95th percentile of anthropometrical data distribution as limits. That is important for the limits of physiological user position. Similarly at least the 95th percentile should be satisfied if looking at the training load of the machines.

Function	Component group	Training machine	Chapter
Ensuring training resistance	Power unit	Q batch 1	3.5.2, 3.5.3
Ensure physiological user position	Seat adjustment	Q Chest Press, Q Seated Rowing	3.5.6
	Back Support adjustment	Q Leg Curl, Q Leg Extension	3.5.5
	Lever arm adjustment	Q Leg Curl , Q Leg Extension, Q Back Extension	3.5.7
Aesthetic product design	Side Mounting, Seat structure	Q batch 1	3.5.8
	Other visible components	Q batch 1	3.5.9

Table 3.5: Overview of concepts

3.5.2. Concept for ensuring training load

The concept of the electric motor in combination with the frequency converter should remain unchanged, so there is no option in changing the concept but only the components. With regard to a lower cost series there is the option for using a motor with less power in combination with a smaller frequency converter. An issue is that just reviewing quantifiable information from the data sheets of different motors from different manufacturers is not the solution. The subjective feeling is a crucial factor and USP for training machines. If a new motor is considered a study has to be conducted to verify the proper feeling with that motor.

By reviewing the machines of the Q series batch 1 upon difference in pivot points, there are two different types. The machines Q Back Extension, Q Leg Curl and Q Leg Extension uses the upper pivot point, while the Q Abdominal Crunch, Q Chest Press and Q Seated Rowing use the lower pivot point. A consideration of changing the motor is only in case of the upper pivot point practical, because the lever arm length in case of the lower pivot point inhibits an usage of a motor with lower torque[57].

Alternative for ensuring training load in lower pivot point

In case of the machines Chest Press and Seated Rowing the gear reduction structure can be removed if the 95th percentile is the limit to be fulfilled and the initial isokinetic strength test remains unchanged (see 3.22 and 3.29). That means that the lever arm can be directly attached to the motor for those two machines and a maximum load of 100 kg can be achieved. The reference is the Q Abdominal Crunch with a direct attachment and a maximum load of 100 kg with an even longer lever arm.

Alternative for electrical motor unit

The current power units in case of upper pivot, i.e. Leg Curl, Leg Extension and Back Extension, can be evaluated. A static investigation is carried out to determine the maximum load possible to train with. By means of a sketch the existing torques are displayed (see figure 3.55).

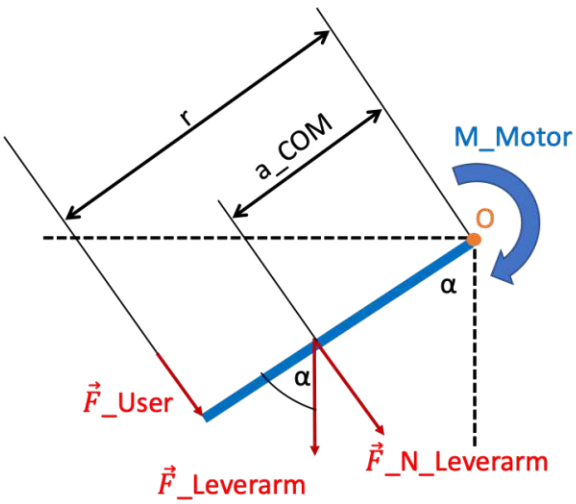


Figure 3.55: Sketch for generic moment calculation[58]

The identified moments around the pivot point O are calculated through force multiplied

[57]personal interview with the head of department on the topic feasibility study as of 19th May 2019
[58]created with Microsoft Power Point as of 15th May 2019

by the lever arm length. The user moment is defined as:

$$M_{User} = \vec{F}_{User} \cdot r \quad [\text{Nm}] \tag{3.1}$$

with:

$\vec{F}_{User}$ User force [N]

r Lever arm length [m]

The lever arm moment is calculated through the gravitational force with respect to the lever arm's center of mass (COM):

$$M_{Leverarm} = \vec{F}_{Leverarm} \cdot a_{COM} \quad [\text{Nm}] \tag{3.2}$$

with:

$\vec{F}_{Leverarm}$ Gravitational force of lever arm [N]

a_{COM} Distance pivot point to COM [m]

Whereby the gravitational force of the lever arm is calculated with:

$$\vec{F}_{Leverarm} = m_{Leverarm} \cdot g \quad [\text{N}] \tag{3.3}$$

with:

$m_{Leverarm}$ Mass of lever arm [kg]

g Gravitational acceleration $[\frac{m}{s^2}]$

whereby g accounts for $9.81\frac{m}{s^2}$.
Finally to get the lever arm force acting on the normal the calculation is:

$$\vec{F}_{N\_Leverarm} = \vec{F}_{Leverarm} \cdot g \cdot sin(\alpha) \quad [\text{N}] \tag{3.4}$$

with:

α Varying leverarm angle (see figure 3.55)

The investigation is carried out for the worst case scenario meaning the maximum existing moment counteracting on the motor is calculated. Therefore an angle of $\alpha = 90°$

is chosen for the calculations below, because the sinus term gives the maximum value in that case.

An equilibrium of moments can be formed through:

$$M_{Motor} = M_{User} + M_{Leverarm} \quad [\text{Nm}] \tag{3.5}$$

A comparison of different motors can be done to determine if a less powered motor unit can be an alternative (see figure 3.56). Calculations are done for the identical lever arm of the machines Q Leg Curl, Q Leg Extension and Q Back Extension. Since the lever arm is adjustable the maximum possible length is taken to display the worst case.

			A	B	C
Variable	**Description**	**Unity**	**Q batch 1 Motor**	**Q batch 3 Motor**	**New motor**
M_drive	Motor drive torque	[Nm]	9,91	5,03	5,03
i	gear ratio	[]	65,50	46,23	69,43
M_output	output torque	[Nm]	649,09	232,51	349,22
	overload factor	[]	1,50	1,50	1,50
M_outputmax	maximum output torque	[Nm]	**973,64**	**348,77**	**523,83**
n_drive	drive rotation speed	[1/min]	1445,00	1425,00	1425,00
n_output	output rotation speed	[1/min]	22,06	30,83	20,53
r	max. lever arm length	[m]	0,45	0,45	0,45
m_leverarm	mass lever arm	[kg]	16,52	16,52	16,52
a_COM	center of gravity from pivot point	[m]	0,31	0,31	0,31
α	worst case angle	[°]	90,00	90,00	90,00
F_User	User Force	[Nm]	2052,55	663,94	1052,96
m_load	max. training load	[kg]	**209,23**	**67,68**	**107,34**
ω_max	max. angle velocity	[°/s]	47,50	47,50	47,50
n_outputmax	max. rotational speed	[1/min]	7,92	7,92	7,92

Figure 3.56: Comparison of different motors with varying gear ratio[59]

Option A is the current motor used for batch 1 of the Q series. Option B is the motor used in batch 3 of the Q series with less power and a different gear ratio. Option C is a solely different motor chosen from the same supplier and not tested upon exercise feeling during training.

The motor drive (input) torque and gear ratio is obtained from the data sheets of the manufacturer. The output torque is calculated through:

$$M_{output} = i \cdot M_{drive} \quad [\text{Nm}] \tag{3.6}$$

[59]created with Microsoft Excel as of 23th May 2019

with:

M_{output} Output torque of motor [Nm]

i Gear ratio [/]

M_{drive} Motor drive torque [Nm]

According to DIN66034-1:2001-02 all motors can be overloaded up to 120 seconds with a factor of 1.5 for the nominal current [11]. The factor of 1.5 is multiplied with the output torque resulting in the maximum possible output torque used for the machines. The output rotation speed is calculated through

$$n_{output} = \frac{n_{drive}}{i} \quad [\frac{1}{min}] \tag{3.7}$$

with:

n_{output} Output rotation speed of motor $[\frac{1}{min}]$

i Gear ratio [/]

n_{drive} Motor drive rotation speed $[\frac{1}{min}]$

According to the equations 3.1, 3.2, 3.5 the force for the user respectively maximum training load can be calculated. Furthermore, additional information for the lever arm (length, mass, COM) is needed. As the lever arm for Back Extension, Leg Curl and Leg Extension is the same, the calculation can be applied to all three machines. The maximum rotational speed needed to move the lever arm is calculated using the widest possible ROM and the shortest occurring training time. The maximum occurring angle velocity consequently is:

$$\omega_{max} = \frac{ROM}{T_{max}} \quad [^{\circ}/s] \tag{3.8}$$

with:

ROM Absolute angle of ROM [$\circ$]

T_{max} Lever arm's fastest time to move through ROM [s]

The maximum angle velocities for the machines with the upper pivot point is displayed in table 3.6.

Machine	ROM[°]	T_{max}[s]	ω_{max}[°/s]
Q Back Extension	95	2	47.5
Q Leg Curl	85	2	42.5
Q Leg Extension	95	2	47.5

Table 3.6: Maximum angle velocities in training[60]

The motor comparison is displayed in figure 3.56 and shows that the maximum angle velocities can be achieved by all three motors.

	95th percentile		
Machine	IKM value [kg]	Eccentric Training Load [kg]	Concentric Training Load [kg]
Q Back Extension	89	61	48
Q Leg Curl	68	37	30
Q Leg Extension	83	49	38

Table 3.7: Upper pivot point machines: 95th percentile of loads[61]

Table 3.7 displays the 95th percentile of all users with respect to IKM and training weight.
If just evaluating the IKM value the batch 3 motor (option B in figure 3.56) can be seen as not sufficient to ensure the proper load to satisfy the 95th percentile of all users. That is in the case if the isokinetic parameters in the IKM remains unchanged.
The new chosen motor (option C in figure 3.56) is sufficient, but a further investigation upon exercise feeling during training needs to be carried out.

A further crucial issue that has to be stated regards the norm tests. The training machines have to be constructed to withstand certain forces, which are stated in the in the norm ISO20957-2:2005-12. The strength training machine has to withstand extrinsic loading. According to the point 5.2.2.2 using the maximum load of the machine (G) and the force determined by the proportional body mass (G_K) following formula is formulated [23]:

$$F = [G_k + 1.5G] \cdot 2 \cdot 9.81 \frac{m}{s^2} \quad [N] \tag{3.9}$$

[60]JSON extraction from Software Development department as of 20th May 2019
[61]based on Data extraction from milon Care as of 5th March 2019

with:

G	maximum load of machine [kg]
G_K	force determined by the proportional body mass (100 kg) [kg]
1.5	dynamic coefficient
2	safety coefficient

If the machines' maximum load decreases, the norm test consequently has to be carried out with less force. The components that are involved in withstanding those forces (e.g. lever arm, seat structure) can be designed with lower strength and stiffness according to material and construction.

Table 3.7 reveals that the training load values are much lower than the respective maximum strength value. The IKM is normally carried less often than the actual training with the respective training loads. If there is the possibility to refer the maximum load as maximum training load, instead of the IKM value, there is a great potential for cost reducing effects (less powered motor, smaller frequency inverter, norm tests). The best case will be using the batch 3 motor, which is already tested upon exercise feeling and currently used for the batch 3 machines. That would decrease variability in motor types and create synergy effects (see chapter 3.5.1).

In conclusion an investigation for alternative training load determination is made to utilize this potential.

3.5.3. Alternatives for training load determination

1RM calculation basis

The current isokinetic one rep max measurement is based on a peak determination. Meaning that the user performs the movement within his individual ROM and the software detects the highest value in a particular angle. Consequently the values for other angles are neglected. In the worst case the user can perform the movement in a manner in which he just gives a high impulse in a particular angle. The calculated value would falsify the load determination for his training.

An alternative way is calculating the maximum load with the average calculation of an integral:

$$\bar{f} = \frac{1}{b-a}\int_a^b f(x)dx \tag{3.10}$$

with:

$\bar{f}$	average value of one measurement
a	individual ROM start value
b	individual ROM end value
$f(x)$	function for measured force curve of user

In this manner all values for the individual ROM of the user are considered and peak values are compensated.
Additionally, the current parameter of angle velocity can be considered upon alteration. Currently the angle velocity ranges from 6°/s to 15°/s (see chapter 3.2.2). Several studies using isokinetic test for strength measurement showed that an increased angle velocity resulted in a decreased muscle torque [2, 33].
Both measures will result in a smaller IKM value for the user compared with the current calculation basis. Furthermore, a falsified usage of the maximum strength measurement would be prevented. This measure will not likely decrease the individuals maximum strength by a great amount. So an exchange of the 1RM measurement by an alternative method for determining strength values is needed.

Multiple RM calculation basis

As described in chapter 2.3.3 it is possible to predict a 1RM with a multiple repetition measurement. A method with a 5RM measurement is suggested and using one of the prediction equations to calculate the 1RM is seen as very accurate [43]. Furthermore, it outperforms a 7-10RM measurement in case of accuracy [13].
Not only is the risk of injuries decreased [43, 13], but this method has the benefit that the existing software algorithms can still be used to calculate from a 1RM to the training load for the repetitions ranging from 10-15.

3.5.4. Alternatives for training form

In terms of distinguishing between the two product series it can be considered to cut features for the cost reduced product line. The Q series inherits the training forms isotonic and isokinetic. Concentric and eccentric training with fixed loads can be established just like in mechanical machines with weighted stacks. Furthermore, eccentric overloading and adaptive training is possible.
For the new series just establishing isokinetic training will be most beneficial (see chapter

2.2.4). It will differentiate from the current series and is also superior to mechanical machines as they cannot us the isokinetic training form.
Another point is that a maximum strength determination is not required, because this training form is angle velocity based, meaning that the user tries to match the velocity of the moving lever arm. If he uses more force and therefore would perform the movement faster the motor gives resistance to hold the particular angle velocity. Without maximum strength measurement the user can immediately start with the exercise and get used to the movement. As the learning effect is established more force can be used by the user without changing parameters.

3.5.5. Alternative for back support adjustment

The proper physiological training position for the Leg Curl and Leg Extension is ensured when the rotation of axis of the knee and the lever arm are overlapping. Because everyone has an individual femur length, the adjustable back support ensures this position. The back support adjustment for Leg Curl and Leg extension has an adjustment range of 150mm. Findings from the Care Data analysis suggest a broader adjustment range. The consideration to mechanically adjust the seating position can work with different technical solutions. For manually adjusting the seating position a gas pressure spring is favoured over adjusting the seat with a plunger pin, because of the time saving aspect in adjusting and the minimized source of error. Figure 3.57 shows a system with gas pressure spring and continuous adjustment from a competitor named "Proxomed".

Figure 3.57: "compass 530 Beinstrecker/-beuger" from proxomed[62]

The concept for mechanical adjustment was dismissed on the basis of several issues. If using the gas pressure spring with continuous adjustment a further locking mechanism is needed to ensure the same individually fixed physiological user position for every training. As can be obtained from the figures 3.8 and 3.17 the adjustment range is fully utilized and a broader range possibly needed. The knee axis must be in line with the axis of pivot and avoiding false forces to harm the users knee is the top priority. In conclusion a seat adjustment is crucial to ensure the user's physiological training position. In using an electronic system, which stores the user's training position prior adjusted by the coach or therapist, wrong adjustments by the user are prevented. If not removing the auxiliary drive it can be considered to exchange the structure of the seat. By means of reducing components it is considered to relocate the guided rails to the outside meaning eliminating the current cover structure.

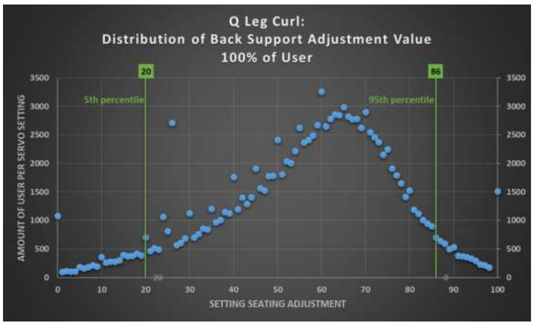
Figure 3.58: Leg Extension precursor product series "Premium"[63]

Before pursuing further steps in developing an alternative concept a cost investigation was carried out with the "Leg extension premium", the precursor series (see figure 3.58). The guided rails were designed on the outside and were positioned below the seat structure. The material costs of the seat structure accounted for 6505.21MC as of 6th January 2016 and can be seen as valid as the premium series was the main product series at that time[64]. By comparison, the seat structure of the current series account for 5948.38MC (see figure A.23). In conclusion there is no cost reduction potential in

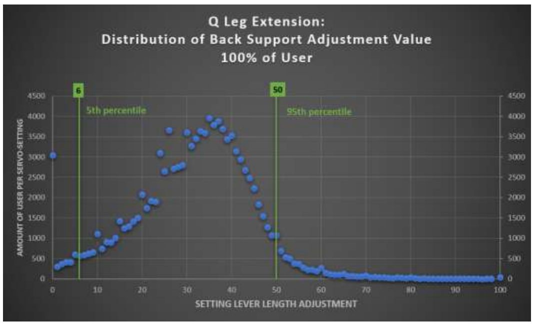
[62]figure retrieved from: `https://www.proxomed.com/de/produkte/compass_530_beinstrecker-beuger-2.html`, last visited 13th May 2019

[63]figure retrieved from: `https://www.milon-brandstore.com/media/?mediaId=0F7547E7-B802-422E-AD90B7A4312C82A9`, last visited 13th May 2019

changing the current construction.



(a) Q Leg Curl



(b) Q Leg Extension

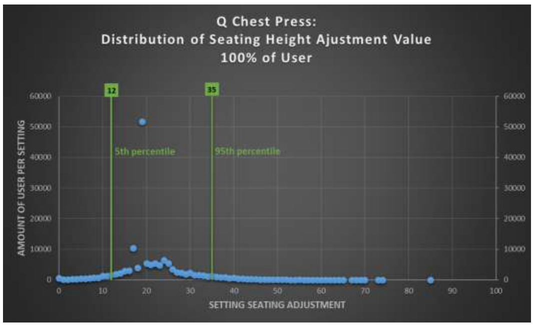
Figure 3.59: Range of 5th and 95th percentile for Q Leg Extension and Q Leg Curl: Back Support Adjustment[65]

Furthermore, the data evaluation (see figure 3.59) show that current adjustment range is sufficient for 5th to 95th percentile of all users. No further investigation was carried out to further pursue an alternative. Nevertheless it can be considered to upgrade the current Q series by expanding the adjustment range.

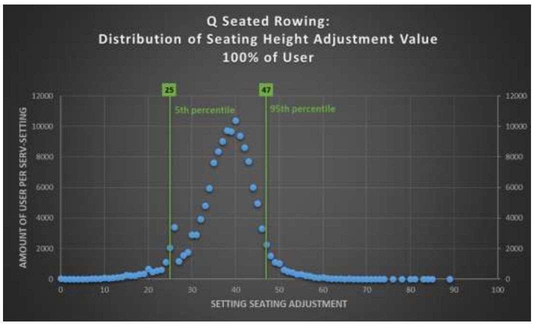
3.5.6. Alternative for seating adjustment

For the machines Q Chest Press and Q Seated Rowing the seating adjustment should ensure a physiological shoulder position. The lifting column for seating adjustment has a range of 400mm, e.g. if divided into the increments of 0 to 100 setting a increase of 1 results in a change of 4mm. The lowest position of the current lifting column is 470.5mm measured between the top edge of the seating cushion and the floor, resulting the highest position being 870.5mm.

[64]technology screening by R&D Department as of 6th January 2016
[65]created with Microsoft Excel based on source: milon Care data extraction as of 5th March 2019



(a) Q Chest Press



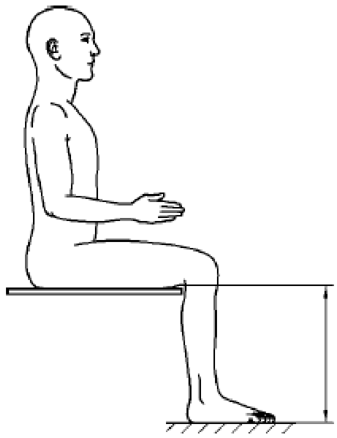
(b) Q Seated Rowing

Figure 3.60: Range of 5th and 95th percentile for Q Chest Press and Q Seated Rowing: Seating height adjustment[66]

Figure 3.60 displays the limits set at the 5th and 95th percentile of the seating adjustment for consideration of further evaluation [9].
The chest press has an adjustment range of 92mm (5th percentile: 12; 95th percentile: 35) and the Seated Rowing 88mm (5th percentile: 25; 95th percentile: 47). If the limits of both machines are matched, i.e. taking the lowest and highest value between the limits 5th and 95th percentile (12 and 47), the range would account for 140mm. This result is in a clear contradiction to the possible adjustment range of 400mm.
The norm further states the issue on irregularity of individual human proportion to be taken into account. Meaning that persons with the same height can have either long legs and a short torso, short legs and a long torso or even proportioned legs and torso [9]. Hence the torso length, more precisely the shoulder height in a seated position can be viewed separately from the seating height, which is mainly defined by the tibia length. The norm DIN33402-2:2005-12 is used to evaluate anthropometric data from German citizens of age 18-65 from the years 1999 to 2002 [10].

[66]created with Microsoft Excel based on source: milon Care data extraction as of 5th March 2019

Tabelle 27 — Länge des Unterschenkels mit Fuß (Sitzflächenhöhe)



Altersgruppen	Länge des Unterschenkels mit Fuß (Sitzflächenhöhe) mm					
	Männer			Frauen		
	Perzentil					
Jahre	5	50	95	5	50	95
18–65	**410**	**450**	**490**	**375**	**415**	**450**
18–25	425	470	505	380	420	455
26–40	410	455	490	375	415	450
41–60	405	445	485	370	410	445
61–65	400	440	480	365	405	440

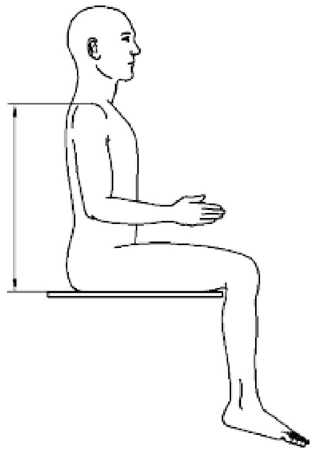
Figure 3.61: 5th to 95th percentile range of seating height [10, p. 33]

Using the findings from the data analysis from milon Care the machines lowest seat position of 470.5mm and an adjustment range of 140mm will result in a top position of 610.5mm as maximum. That would satisfy the 5th to 95th percentile of users for both machines (Chest Press and Seated Rowing). But evaluating the percentiles of lower leg lengths from DIN33402-2:2005-12 depicts a quite different picture (see figure 3.61). If taking all age groups and gender into account the bottom position (5th percentile) will be 375mm and the top position 490mm. That signals a drastic shift of the whole range towards the bottom position.

It has to be stated that the seating height adjustment of the two milon strength machines Q Chest Press and Q Seated Rowing are constructed towards an adjustment of solely the upper body. Meaning that the grip position, and therefore shoulder height and arm length, is the decisive factor when adjusting a correct physiological training position for the user. So it might be possible for small persons to have no contact to the floor with their feet to satisfy a safe shoulder position. DIN33402-2:2005-12 on the other hand just takes the length of the lower limb into account.

If the seat height is considered to be fixed rather than adjustable a proper seating height that suits most user has to be defined. According to DIN33402-2 Bbl 1:2006-08 the seating height should be shifted towards the 5th percentile rather than using the median. User with long shanks can put their feet further away from the seat to be in a physiological position. That would result in choosing a fixed seat height between 375mm and 410mm if taking all age groups and gender into account. But choosing a too low seat height would decrease usability for tall people and the elderly, as it can be challenging for them to stand back up from a too low seat position. Finally, further studies should be carried out upon a proper fixed seat height which also satisfy usability.

Tabelle 24 — Schulterhöhe, sitzend



Altersgruppen	Schulterhöhe, sitzend mm					
	Männer			Frauen		
	Perzentil					
Jahre	5	50	95	5	50	95
18–65	**570**	**625**	**670**	**540**	**590**	**630**
18–25	590	640	685	560	600	640
26–40	575	630	675	545	595	630
41–60	565	615	665	535	585	625
61–65	550	605	655	525	575	620

Figure 3.62: 5th to 95th percentile range of shoulder height in seated position[67]

The next factor that has to be looked at when using a fixed seat height is the variety of the upper body more precisely the shoulder height. The shoulder height variety accounts for 130mm, if the range across gender and age is taken into account (see figure 3.62; 5th percentile: 540mm, 95th percentile: 670mm). To offset the difference of 130mm in shoulder height without seating adjustment another concept is needed.

[67]figure retrieved from: DIN33402-2:2005-12 tabular 24, S.30

Figure 3.63: Bended dual grip for Chest Press[68]

The bended dual grip concept allows the user to choose from two grip positions (see figure 3.63). The lower position is intended for people with smaller torso and the upper position for people with longer torso. The grip handles are not horizontal, but slightly angled towards a neutral grip. They imitate the strength exercise bench press with dumbbells rather than with a straight barbell. A benefit is preventing the shoulder to be lifted and activating the m. trapezius during training. With this angled grip the arms are forced to be tucked in. By activating the m. latissimus dorsi the shoulder is fixed in a proper physiological position. Thus allowing the m. pectoralis major and m. triceps brachii to be activated properly, which is intended for that exercise.
For the machine Q Seated Rowing the grips in the current series are already angled. So the new concept is just adding an additional grip.
For the new series the initial set up of the machine consists of adjusting the ROM, as well as choosing the lower or upper grip position. That value is saved for the user in the milon Care software. Another important point to be stated is, that the lever arm length for calculation changes according to the used grip position for the user. The formula will use the longer lever arm length if calculating the proper load if the user's setting is the upper grip position. When storing the lower grip position for the user, the formula uses the shorter lever arm length for calculation. Furthermore, the user has to be informed prior to his training which grip to use. That can be achieved by a message through the display before the user starts the exercise, displaying "upper grip" or "lower grip".

[68]created with Solid Edge, rendering with Key Shot by Luxion as of 9th may 2019

3.5.7. Alternative for lever arm adjustment

The adjustment for lever arm length concerns the machines Back Extension, Leg Curl and Leg Extension.

Figure 3.64: Manual lever arm adjustment[69]

A locking bolt with a spring inside and locking disk with 5 different positions is used (see figure 3.64). By pulling the locking bolt, the lever arm cushion can be shifted and automatically locks into one of the locking pin's holes. This concept is already been proven by the current down holder of the Q Leg Curl.
Comparable to the two grip concept in chapter 3.5.6 the lever arm length changes depending on the used fixing location. Furthermore, the position has to be communicated to the user prior to his training. Another point to improve usability would be marking the locking disk with numbers ranging from 1 to 5, so that the user can detect the right fixing position when he gets the message on the screen instantly.

[69]created with Solid Edge, rendering with Key Shot by Luxion as of 16th may 2019

3.5.8. Alternatives for cost intensive component groups

According to the function cost analysis in chapter 3.4.5 the most expensive function with respect to the weighted comparison is aesthetic product design. Reviewing the component groups that are involved with that function are the seat structure and side mounting.

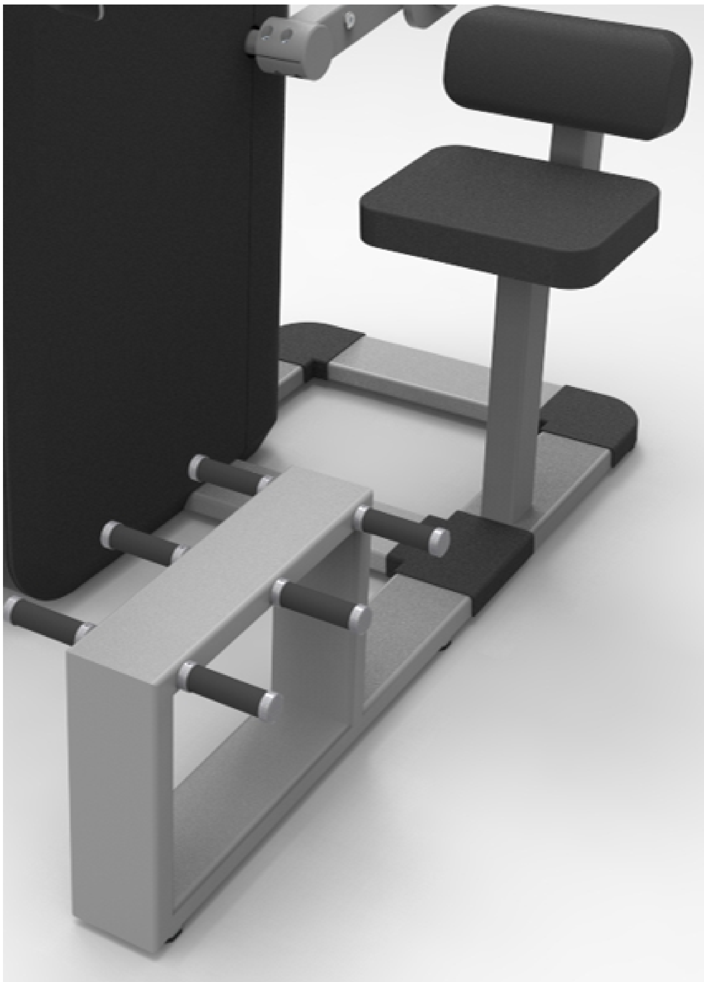


Figure 3.65: Concept Side mounting[70]

The current series uses a combined sheet and tube concept for the side mounting, combined with inserts to cover the surface. So an aesthetic look with bend profiles is achieved. Appropriately the sheets for the seat structure works on the concept of insertable panels which allows for bend designs in different angles.

[70]created with Solid Edge, rendering with Key Shot by Luxion as of 12th may 2019

The new concept for the side mounting and seat structure is to use rectangular tubes for both component groups. The tubes of the foot rest are welded as well as the connection site between seat structure and side mounting. To ensure a bent look for the side mounting injection-moulding parts are constructed which covers the welding area and saves reworking (see figure 3.65).

The casing form need to stay the same, so only a material change can be considered (see chapter 3.5.1)

3.5.9. Solution brochure for other visible components

Some alternatives for visible parts do not result in big architecture change, but nevertheless can in sum have a cost reducing effect on the training machine respectively the whole strength circle.

Component Group	**Change with respect to Q series**
Side mounting, seat structure, lever arm	Change powder coating material
Casing	Change material to Acrylonitrile butadiene styrene (ABS) without Poly(methyl methacrylate) (PMMA) foil or Polystyrene (PS)
Display holder	rectangular profile welded on mitre
Optics: grips	Change grip rings and caps to material ABS
Cushion	Change coating material to artificial leather and use round cushion form
Tray	use single compartment tray from milonizer

Table 3.8: Concepts for other visible components

Table 3.8 sums up all concepts regarding smaller changes which will also have a cost reducing and distinguishing effect.

3.6. Concept evaluation

Evaluation of the concepts consists of a feasibility analysis with the head of Research and Development (R&D) department and a cost estimate with the head of purchasing department upon consultation with the corresponding manufacturers. The cost estimate will be graded with an internal definition displayed in table 3.9.

Grade	Description
HG1	Estimated costs from purchase department
HG2	Verbal target price from supplier, alternative prototype price
HG3	Written target price from supplier, alternative pilot series price
HG4	Offer for series production from supplier
HG5	Price of series after reaching sales volume

Table 3.9: Internal grading system for cost estimate

For each concept, which were identified as feasible, a graded cost reducing potential is identified. Figure 3.66 shows all general measures and potentials for the strength training devices of batch 1. In the next step those measures are applied to each machine (see appendix A.5).

Strength training machines batch 1					
Measure	Grade	Component	Change with respect to Q	Potential	Unit
1	HG1	Side mounting, seat structure	welded rectangular profile with PA66 cover, without inlay cover	-2331.66 to -5642,83	MC/Machine
2	HG1	Optics: Side mounting, set structure, lever arm	change powder coating material to tiger drylac RAL9005	-44.41 to -55.52	MC/Part
3	HG1	Casing	casing material standard ABS without PMMA foil	[redacted]	MC/kg
4	HG1	Display holder	display connection rectangular profile without casing	none	MC/Machine
5	HG1	Lever arm	no auxiliary drive, locking bolt and disc	-980,96	MC/Machine
6	HG2	Lever arm connection	direct lever arm connection	-1.622,72	MC/Machine
7	HG2	Optics	change grip caps material to ABS	[redacted]	MC/Part
8	HG2	Optics	change grip rings material to ABS	[redacted]	MC/Part
9	HG2	Cushion	change coating material to artificial leather	-55.52 to -66.62	MC/Part
10	HG3	Cushion	round cushion lever arm	-63,95	MC/Machine
11	HG3	Power unit	change to bevel geared motor from batch 3	[redacted]	MC/Machine
12	HG3	Tray	tray from milonizer	-65,51	MC/Machine
13	HG3	HMI	no pulse receiver	[redacted]	MC/Machine

Figure 3.66: General cost estimate for concepts of batch 1 strength training machines[71]

[71] created with Microsoft Excel as of 12th June 2019

According to the proper handling of sensitive company data (see chapter 3.4) no supplier name will be published and the cost saving potential regarding certain components will be masked.

(1) Measure 1 refers to the concept described in chapter 3.5.8. The cost estimate for the simplified construction has got a price range depending on the machine. The Q Abdominal Crunch and Q Back Extension with footrest will be at the higher end of the cost potential because of the additional structures. The covers from injected moulding parts are seen positive by the manufacturer as he would save time to rework the welding areas. For the machines Q Chest Press and Q Seated Rowing the lifting column will be removed, therefore they have the highest cost saving potential for this measure.

(2) Measure 2 describe the change in material for powder coating. Liquid coating as well as structure paint will not have a cost reducing effect. Thus the only measure is to change the powder coating material. If using a more standard material without sparkling effect like RAL9005 there is a cost reduction potential. The smaller parts like lever arm and seat structure will be at the lower end and the side mounting at the higher end of the cost saving range.

(3) Measure 3 refers also to optics but describes a change in casing material. From the results in chapter 3.5.1 a form change of the frame and casing parts is not beneficial. This leads to the conclusion that only the casing material is changeable. According to the manufacturer using PS will not have a good price performance ratio. It can be considered to change to a standard ABS material without PMMA foil.

(4) Measure 4 is changing the current display connection to the frame with welded sheets and a cover to a rectangular profile. The manufacturer doesn't recognize a great cost saving potential. Furthermore, there could be problems in cable routing in assembling the machine in the production resulting in the dismissal of this concept.

(5) Measure 5 refers to a change in Lever arm. For the machines Q Leg Curl, Q Leg Extension and Q Back Extension the concept is described in chapter 3.5.7. In that case the auxiliary drive is removed and a locking pin and disk added. For the machines Chest Press and Seated Rowing there are additional costs as the grip structures become more bent.

(6) Measure 6 refers to the machines Q Chest Press and Q Seated Rowing regarding a load reduction described in chapter 3.5.2. The lever arm is directly connected to the motor without the gear reduction structures.

(7) Measure 7 refers to a material change for the grip caps using the ABS material from the precursor series resulting in a small cost reduction potential.

(8) Measure 8 to the same material change as described in measure 7, but refers to the grip rings. Both measures show a small cost reducing potential, but are important for a optical distinguishing effect from the current series.

(9) Measure 9 refers to a change of the cushions. The stuffing made of recycling material is already at the lowest cost, resulting in the only change to be made for the coating material. The cost reduction range of a change to synthetic leather is dependent on the size of the cushion.

(10) Measure 10 refers to the machines Q Leg Curl, Q Leg Extension and Q Back Extension and using round shape instead of oval shape.

(11) Measure 11 refers to a possible load determination change described in chapter 3.5.3. If the concept is implemented a change to the less powered motor of batch 3 can be made.

(12) Measure 12 has an cost reducing and distinguishing effect by using the already existing one compartment tray of the machine Milonizer.

(13) Measure 13 is removing the pulse receiver, which is more relevant for the cardio machines and create a further differentiation to the current product series.

4. Results

4.1. Visualization of the cost reduced series

The current series is termed with the letter Q, consequently the new series will also be given a specific letter. Due to the fact that the majority of the structures are fixed compared to the Q series the new series will be given the **letter S**, which can be associated with the word **solid**.
Two machines, the S Chest Press and the S Back Extension, will be visualized to provide an insight into how the new series could be designed.

4.1.1. Visualization S Chest Press

The casing color will be implemented in white giving a contrast to the RAL9005 side mounting, seat structure and the black cushion and side mounting covers. Figures 4.1, 4.2 and 4.3 show the design concept of the new Chest Press machine from different point of views.

Figure 4.1: Final Concept S Chest Press - left front view[72]

The grips are slightly angled downwards and show two positions to place the hands. The lifting column is exchanged for rectangular tube profile and the Tray consists of one compartment for a single bottle.

Figure 4.2: Final Concept S Chest Press - right top view[73]

[72]created with Solid Edge, rendering with Key Shot by Luxion as of 30th may 2019
[73]created with Solid Edge, rendering with Key Shot by Luxion as of 30th may 2019

Figure 4.3: Final Concept S Chest Press - left back view[74]

[74]created with Solid Edge, rendering with Key Shot by Luxion as of 30th may 2019

4.1.2. Visualization S Back Extension

Like for the S Chest Press all machines will have uniform colors for different component groups. The footrest is made of rectangular profiles welded on mitre with the same angle as the frame construction. The design concept of the new Back Extension machine can be seen in figures 4.4, 4.5 and 4.6 from different point of views.

Figure 4.4: Final Concept S Back Extension - left front view[75]

[75]created with Solid Edge, rendering with Key Shot by Luxion as of 30th may 2019

The seat structure is simplified with rectangular profiles. The form of the lever arm cushion is changed to a circular shape and the adjustment for the lever arm is exchanged for a manual adjustment mechanism consisting of a locking bolt and disk.

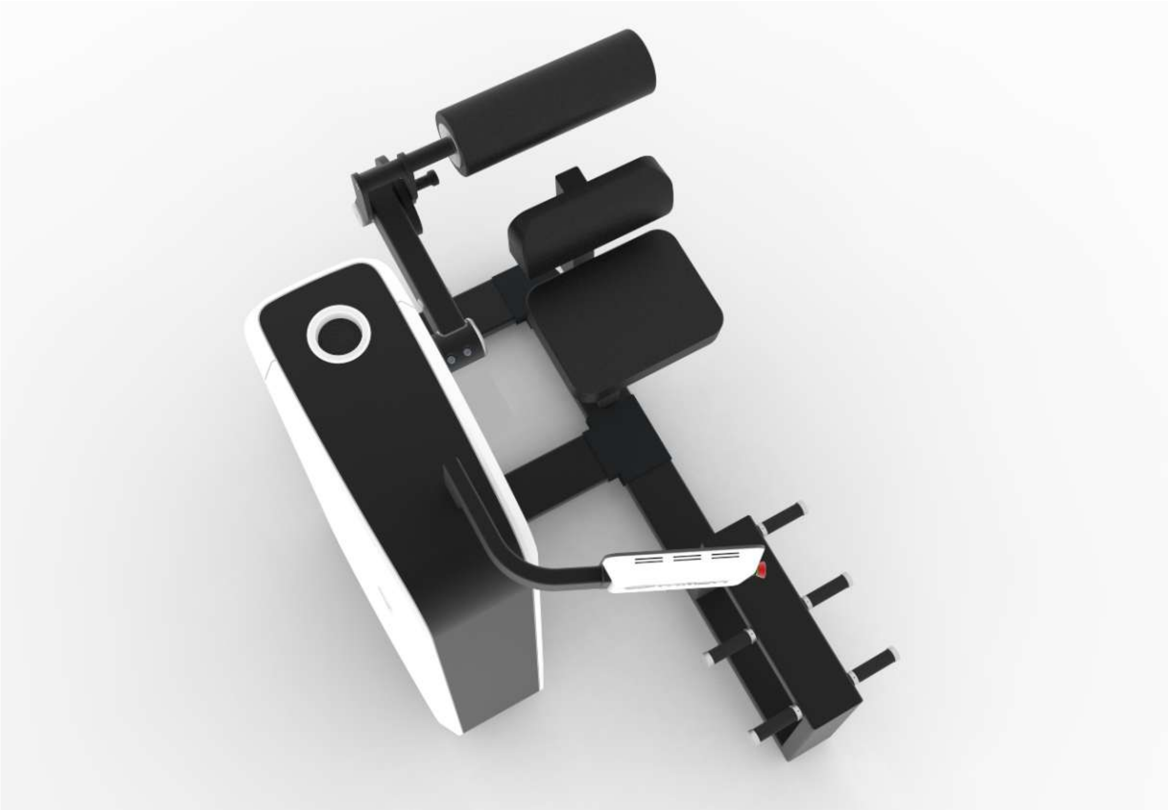


Figure 4.5: Final Concept S Back Extension - right top view[76]

[76]created with Solid Edge, rendering with Key Shot by Luxion as of 30th may 2019

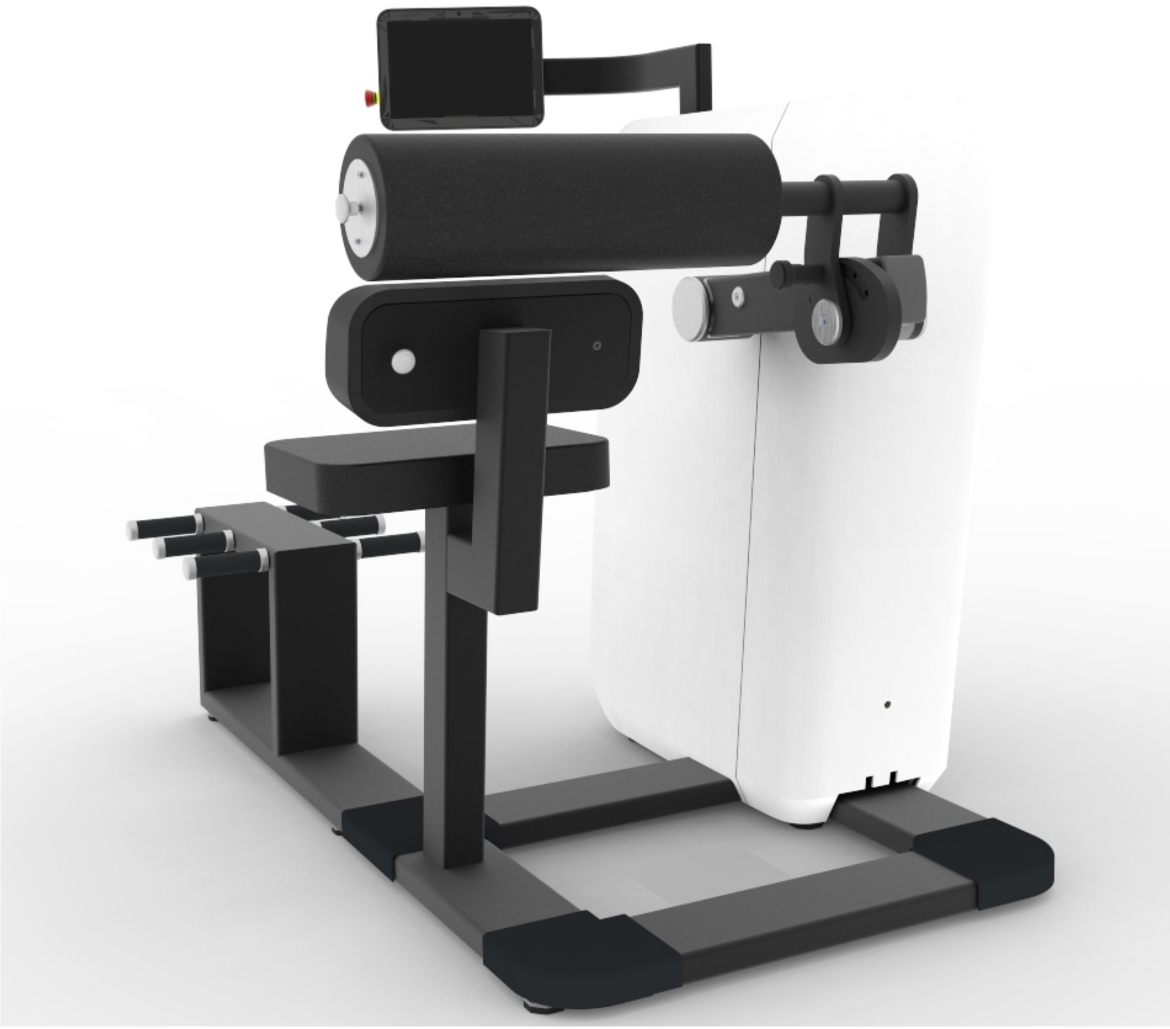


Figure 4.6: Final Concept S Back Extension - left back view[77]

[77]created with Solid Edge, rendering with Key Shot by Luxion as of 30th May 2019

4.2. Distinction from current product series

Additionally, to the change of architecture and alternative components following features are proposed for the two series to prevent cannibalization effects. To further differentiate from the S series upgrading the Q series should be considered.
As found out in chapter 3.3.9 the lever arm of the Q Leg Curl, Q Leg Extension and Q Back Extension needs an extension of adjustment range as well as the back support for the Q Leg Curl and Q Leg Extension. However, the results from chapter 3.3.10 show that the current adjustment range is sufficient for the 5th to 95th percentile of users. With the intent that the S series satisfy most of the user needs and the Q series all user needs a broader lever arm and back support adjustment range should be considered for the current Q product series.
Both measures will result in a change of construction, a different auxiliary drive and in increasing the material cost for the Q series. Nevertheless it will be necessary to ensure a proper physiological position and differentiate from the S series.

Figure 4.7: "Cardanic grip" of Q Lat Pulldown[78]

For the machine Q Seated Rowing further variety can be created by exchanging the current fixed grip with the grip from the machine Q Lat Pulldown (see figure 4.7). This adds another degree of freedom allowing the user to pull with different grip position with respect to forearm rotation and get different focus of muscle activation. The variation including a pronated grip activating more m. brachialis, a supinated grip focusing more on the m. biceps brachii or a neutral grip for more m. brachioradialis activation [5]. That measure would achieve an upgrade status for the current series

[78]edited figure retrieved from R&D department milon industries GmbH, rendering with Key Shot by Luxion as of 24th January 2019

with respect to the new cost reduced series.

Following upgrades of the Q series should be considered

- Broader adjustment range of the back support of Q Leg Curl and Q Leg Extension
- Broader adjustment range of the lever arm for Q Leg Curl, Q Leg Extension and Q Back Extension
- Cardanic grip for Q Seated Rowing (see chapter 3.5.6 figure 4.7)
- Bigger touchscreen (15 inch instead of 10 inch)
- Change of Graphical User Interface (GUI)

4.3. Cost reducing potential for the new series

By distributing all measures to the corresponding training machines the material cost reducing potential for the six strength machines of batch 1 can be compared (see figure 4.8).

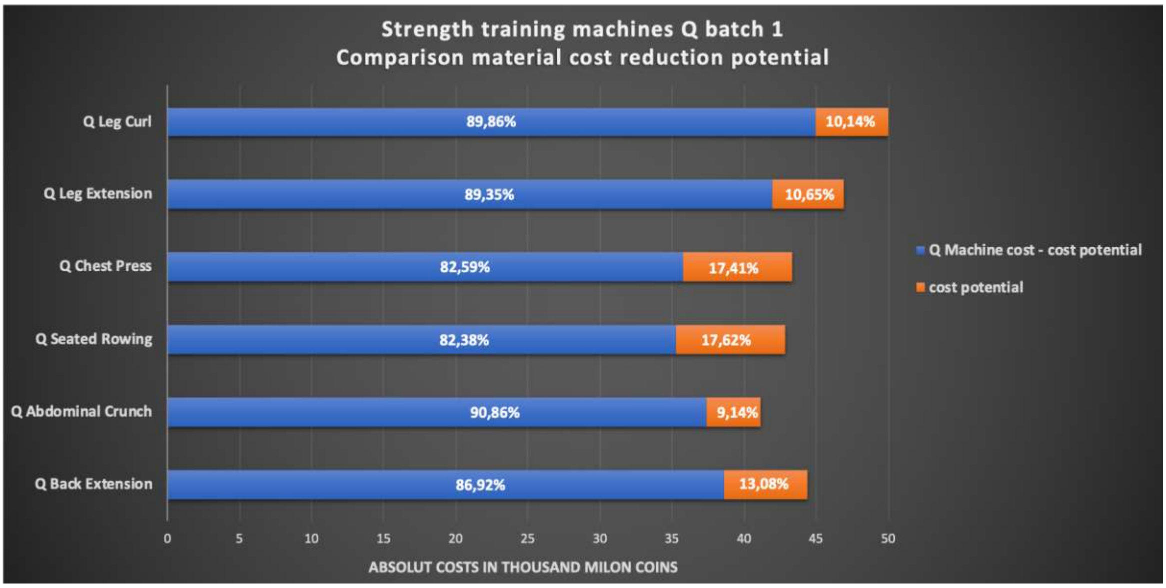


Figure 4.8: Cost reducing potential of the strength training machines of batch 1[79]

(1) The machine Q Leg Curl has the highest material costs, because of the two auxiliary drives and the downholder for fixating the thighs. The material cost reducing potential accounts for 10.14% for the S series as the back support adjustment is unaltered, but the side mounting and the seat structure is simplified. The less powered motor unit used for the batch 3 machines of the Q series is exchanged with the current power unit for the Q Leg curl.

(2) The material costs for the machine Q Leg Extension are lower compared to the Q Leg Curl, because it does not have a downholder. With the same measures as for the Q Leg Curl applied, the potential for reduced material costs fo the new series is at 10.65%.

(3) The machines Q Chest Press and Q Seated Rowing show the highest material cost saving potential of over 17% as the lifting column is eradicated and the side mounting and seat structures are simplified for the new series.

[79]created with Microsoft Excel as of 1st June 2019

(4) For the machine Q Abdominal Crunch, which already has low absolute material costs, a material cost saving potential of 9.14% can be achieved through simplifying the side mounting, foot rest and seat structure.

(5) A material cost saving potential of 13.08% is achieved for the machine Q Back Extension as the side mounting, foot rest and seat structure is simplified. Furthermore the auxiliary drive for the lever arm is exchanged with a manual mechanical adjustment. A less powered motor unit is used just like for the S Leg Curl and S Leg Extension.

The total material cost saving potential of the batch 1 strength circle is calculated through the average material cost reducing potentials of all six strength machines. The total decrease of material costs accounts for 12.93% for the new S series with respect to the current Q series.

4.4. Modular product design

The frame construction was identified for being the platform at which the other components connects through interfaces. Consequently the form of the casing will stay the same and just a change of material is realized. In case of the power units and frequency inverter pair there are only two types implemented throughout the two series'. The control cabinet construction stays the same and just vary in number of circuit boards according to the number of adjustments possible for the respective machine. The architecture of the seat structure, side mounting and lever arm is changed. In case of optics the S series will inherit one color for cushion and casing and the current display, whereby the Q series will increase its' display size and have different cushion and casing colors freely selectable by the customer.

Benefits of purchasing in higher batch size can be achieved by using identical parts for both series'. Furthermore, the same interfaces or connecting sides are used to prevent an increase of production time. A classical learning curve is not established, because the assemblers are familiar with the processes of the current product series.

Figure 4.9 illustrates the modules for both series. Each line can be understood as if boxes in that line share the same color the respective module is the same.

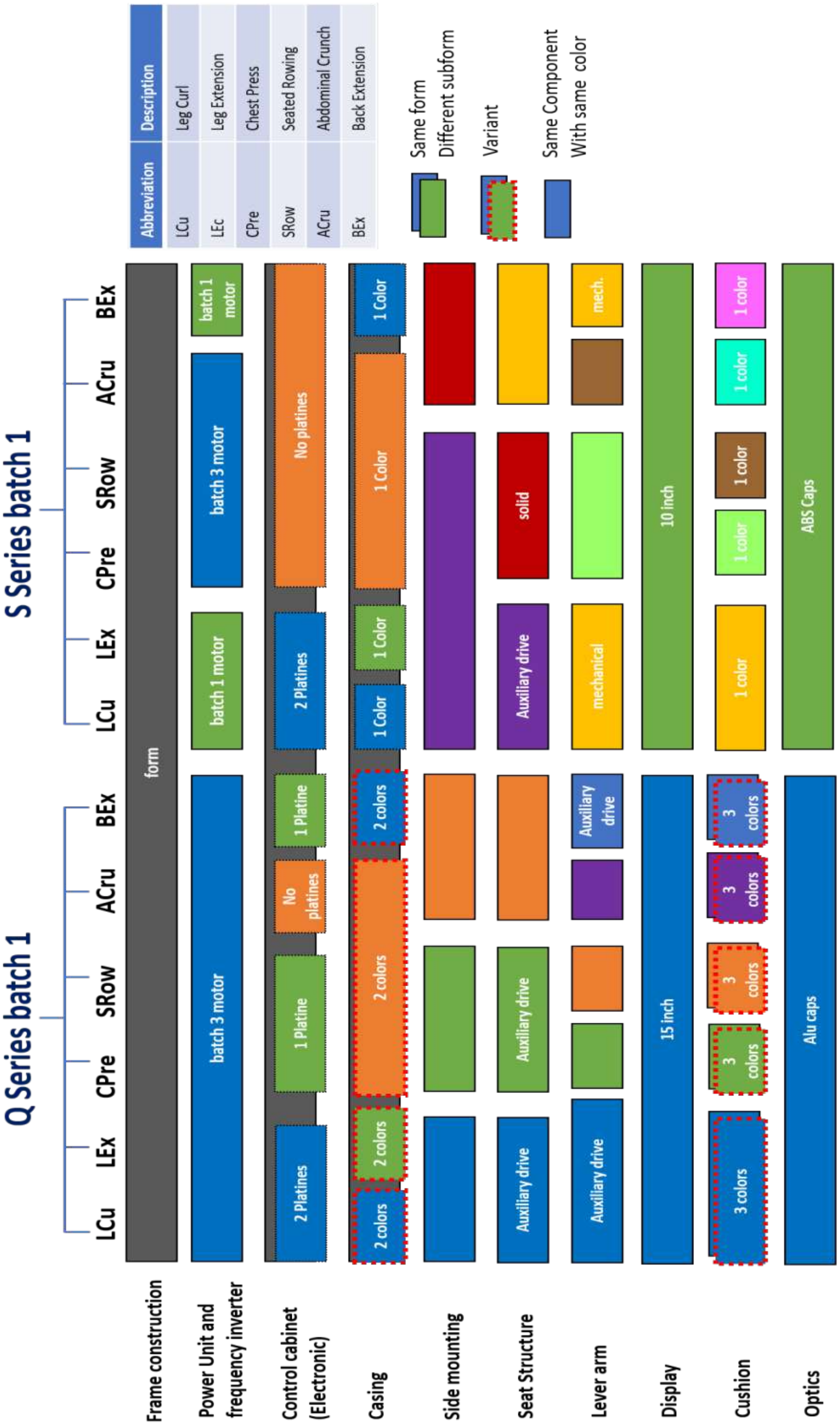


Figure 4.9: Overview modules of both series[80]

[80]created with Microsoft Power Point as of 03th June 2019

5. Discussion

The evaluated data sets show a big discrepancy between maximum strength value and actual training weight. That arises from the fact that a one repetition maximum is calculated towards a 10-15 repetition range for training. Several issues arise with the current way of strength value measurement. The risk of harming tendons and ligaments, especially for untrained persons and the elderly must be considered. Moreover, it is difficult particularly for users inexperienced in strength training to use maximum strength on a new movement. Apart from that the IKM uses the peak value to determine the user's individual maximum strength value (1RM), meaning that just the highest value over the user's individual ROM is taken neglecting the other values from the other angles for calculation. It is therefore possible for the user to get a higher maximum strength value by just giving an impulse in an arbitrary angle position of the lever arm instead of using maximal effort over the full ROM. To prevent this kind of incorrect use it should be considered to change the calculation basis for the IKM. An integral calculation over the curve instead of a peak value determination can be used. In addition to this, a proposed 5RM instead of the current 1RM determination procedure will bring many benefits (see chapter 3.5.3). The existing algorithms can be used as the 5RM can be easily calculated towards a 1RM using the prediction equations in chapter 2.3.3.

Another aim was to show through data evaluation what loads the users actually utilized for their training. The low training loads in comparison with the maximum strength value result in a new concept for training load determination regarding the new product series. It makes sense to establish a distinguishing effect by having different maximum loads for the machines of the two series. Furthermore, it is logical that the cost reduced series will inherit a lower load maximum. Not only can a less powered motor with lower cost be considered, but the benefits include the issue of norm testing as described in chapter 3.5.2. All components that are exposed to forces generated by the machine or the user need to withstand deformation and failure with a dynamic and security factor. This calculation includes maximum user weight and maximum additional load. By reducing at least one, the maximum load for testing can be reduced to a great amount. Consequently, the components require to endure lower loads and construction complexity as well as material costs can be reduced.

Another point was to determine the extent of adjustments range utilized by the user. For the machines Q Chest Press and Q Seated Rowing, it was determined that the possible range of 400mm was not exploited. Therefore, another way was found to ensure physiological user position by focusing on the shoulder height in a seated position. It was concluded that a range of 140mm is sufficient to include all users from 5th to 95th percentile. The data analyses showed that for the machines Leg Curl, Leg Extension the back support adjustment range needs to be expanded. Reviewing the 5th to 95th percentile the current adjustment will be sufficient for the S series, but with the intent of satisfying all users, an extension of the adjustment rage of the current Q series should be considered. The lever arm length adjustment for the machines Q Leg curl, Q Leg Extension and Q Back Extension should be handled in the same manner.

In implementing all the concepts, a cost saving potential of about 12.93% can be achieved for the new product series. Furthermore, following the modular structure (see figure 4.9) synergy effects will be generated, i.e. purchasing of identical parts for both series in higher batch sizes. A further benefit is that there will be no classical learning curve, and the production time for the workers will not be increased to a great amount when establishing the new product series.

An upgrade of the current Q series upon proper loading and adjustment range to ensure the user's physiological training position should be executed to create additional differentiation between the two series. That will likely result in higher material costs for the Q series. In terms of product design an upgrade of the GUI as well as a larger display can be considered for the current product series Q.

Before implementing the concepts for a new product series, a further investigation needs to be carried out regarding usability and ensuring the user's physiological training position. Several concepts like the two-grip lever arm or seating height for the machines S Chest Press and S Seated Rowing need to be investigated in detail upon proper length measurements.

6. Conclusion

It is possible to use specific biostatistical data to evaluate the efficacy of strength training machines. The queried data sets represent each user's maximum values for the isokinetic maximum strength test and their currently used concentric an eccentric training loads. Furthermore, the ROM and servo settings are also important key factors. Conclusions could be drawn on alterations of the current strength training machines to improve their performance in satisfying the customer needs. This is done by adapting maximum loading of the machine and the adjustment range of the seating or lever arm structures to ensure a physiological training position for the user.
The second task was to use those data sets to obtain a new cost reduced product series. This is achieved in using the limits of 5th and 95th percentile regarding adjustment settings for physiological training position. Certain structures like the lifting column for the Q Chest Press and Q Seated Rowing machines could be eliminated as their actual used adjustment range is much smaller than their possible adjustment range. For maximum load of the machines the lower limit was set at the 95th percentile. The 95th percentile loads of the IKM cannot be reached with the less powered motor, so an alternative load determination is suggested. A 5RM instead of a 1RM test is used to decrease the maximum load. Alternative cost reduced components like a less powered motor unit (from the batch 3 strength machines) or the concepts for fixed seats (without an adjustment motor unit) could be implemented, which result in an estimated material cost reduction potential for the batch 1 strength training machines of 12.93%.
Simplified structures were used to reduce material cost and at the same time ensure a differentiation between both product series. The concept for the product variant is created with the intention to establish a cost reduced product series that won't cannibalize the current product series. Furthermore, the new cost reduced S series is intended to be integrated into existing production processes without increasing time and costs to a great amount by using identical connections sites with respect to the current Q series and utilizing existing production processes.
Before implementing the concepts regarding the user's training position an investigation into proper measurements should be done. Further data queries should be considered reviewing users' training progression to evaluate the current training concepts.

7. Suggestions for further research

The gathered data stored with the software milon Care is a powerful tool to gain knowledge about training habits of the users. For this Master's thesis data sets were queried, with the aim to determine which loading and adjustment ranges are utilized by the users. User data regarding gender, age, training target were not investigated. A high IKM value compared with the training load value could be identified, but no conclusions about the user's training progression could be made just with those data sets. Further studies could give an insight into how a user progresses when training with milon strength machines. Therefore, a group of users with different training targets can be chosen. To conduct the study, they should have performed several strength measurements throughout a longer period of time (e.g. more than one year) to assure if the current training concept is suitable for an increase of muscle volume and therefore strength gain. Moreover, differences for age groups, gender and training target could be pointed out. Another possibility would be analysing reference loading and ROM values for specific age groups. On the one hand these are valuable pieces of information for the company regarding further product developments, on the other hand the trainer or therapist can be provided with information to improve customer care. Finally, the user himself is able to use the provided data for instance to compare his fitness level with others in his age group. There is the possibility that user, who are situated at the bottom of their age group upon this comparison, get demotivated to further train. However, this data access can be a motivational tool for the user to consistently train to improve strength and get better.

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A. Appendix

A.1. Data analysis on basis of raw data from milon Care

Data Analysis Q Lat Pulldown

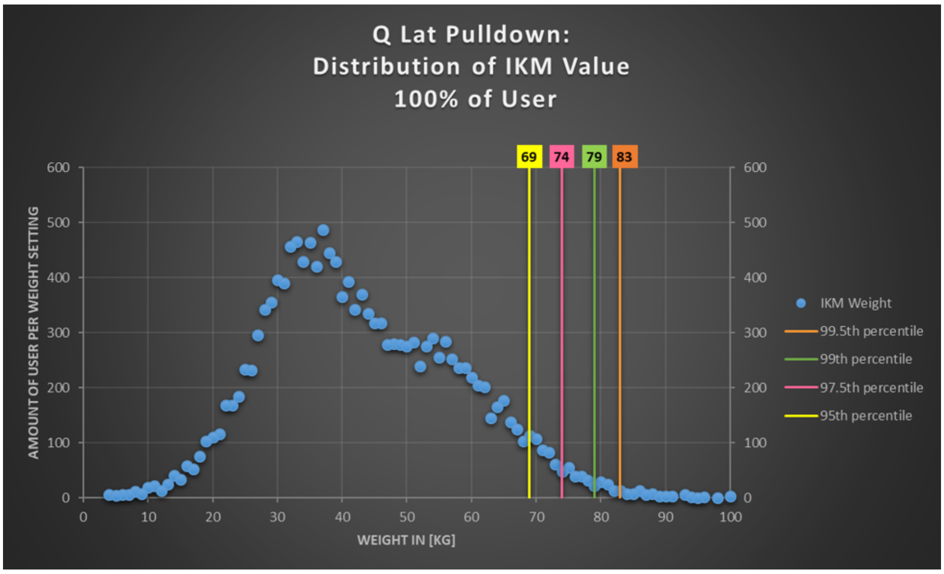

Figure A.1: Maximum strength distribution Q Lat Pulldown[81]

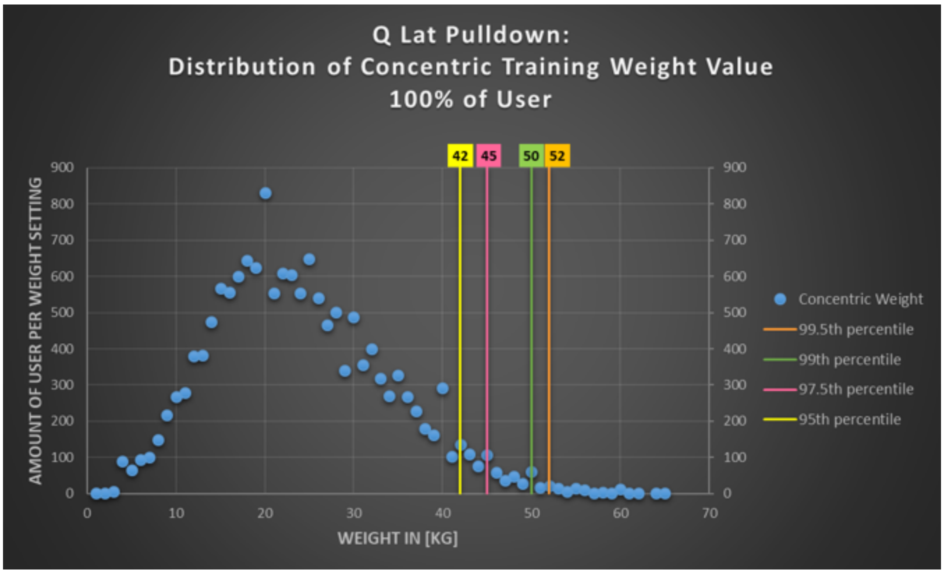

Figure A.2: Concentric training weight distribution Q Lat Pulldown[82]

[81]created with Microsoft Excel based on source: milon Care data extraction from 5th march 2019
[82]created with Microsoft Excel based on source: milon Care data extraction from 5th March 2019

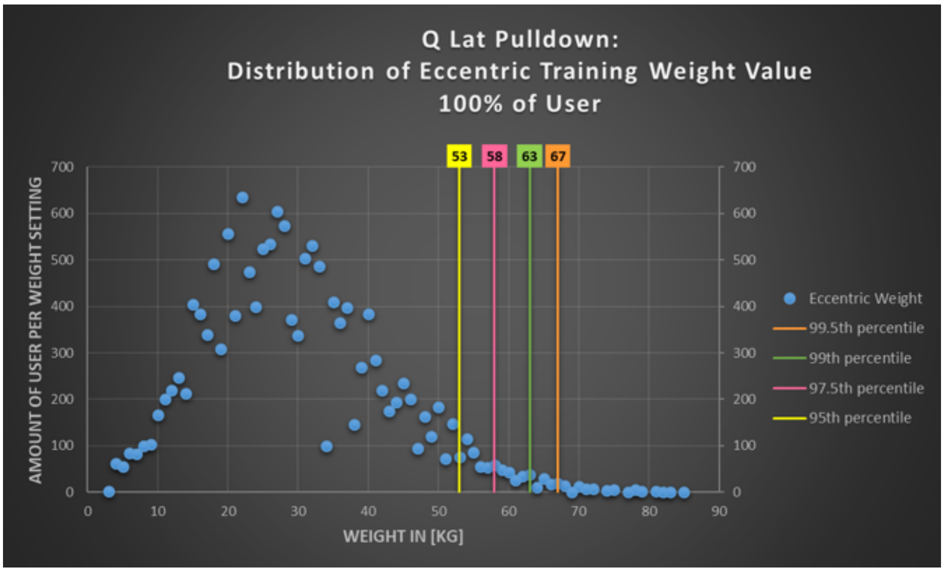

Figure A.3: Eccentric training weight distribution Q Lat Pulldown[83]

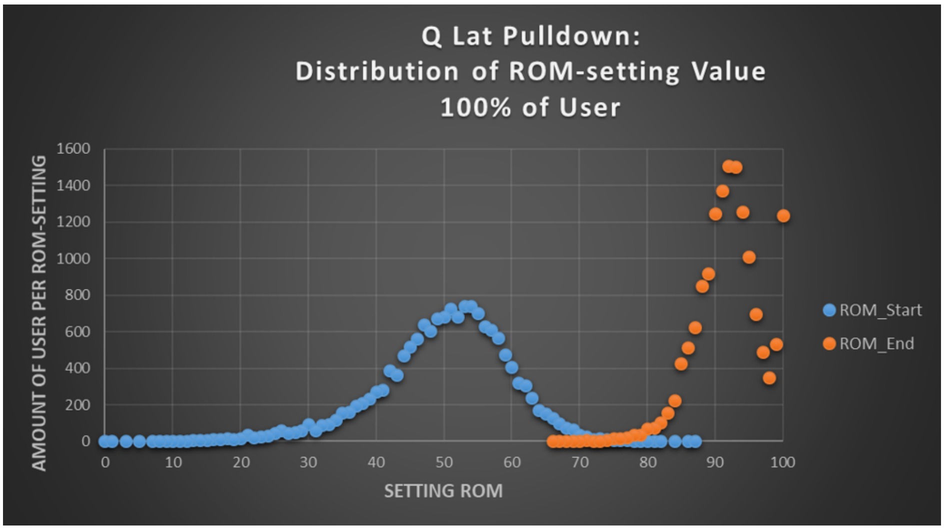

Figure A.4: ROM distribution of Q Lat Pulldown[84]

[83]created with Microsoft Excel on source: milon Care data extraction from 5th March 2019
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Data Analysis Q Shoulder Press

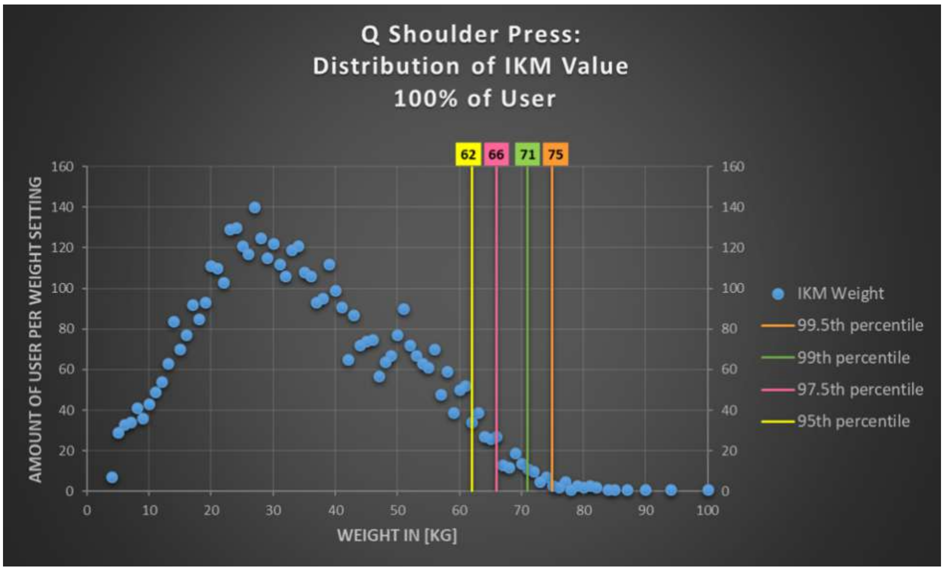

Figure A.5: Maximum strength distribution Q Shoulder Press[85]

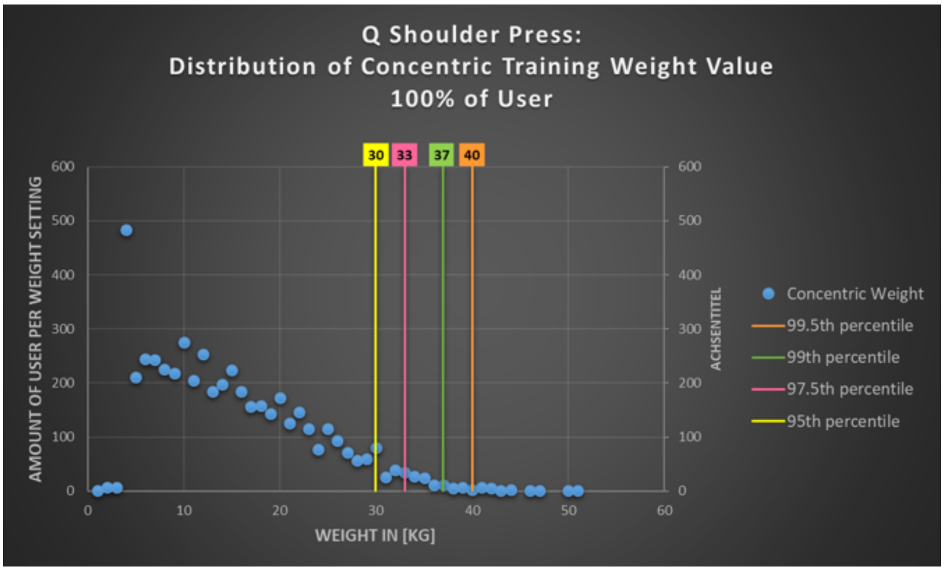

Figure A.6: Concentric training weight distribution Q Shoulder Press[86]

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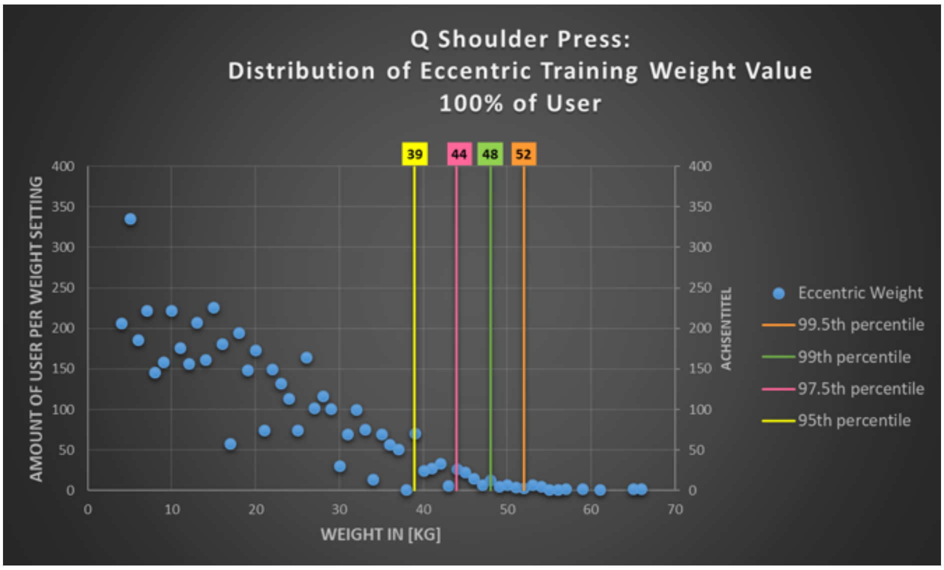

Figure A.7: Eccentric training weight distribution Q Shoulder Press[87]

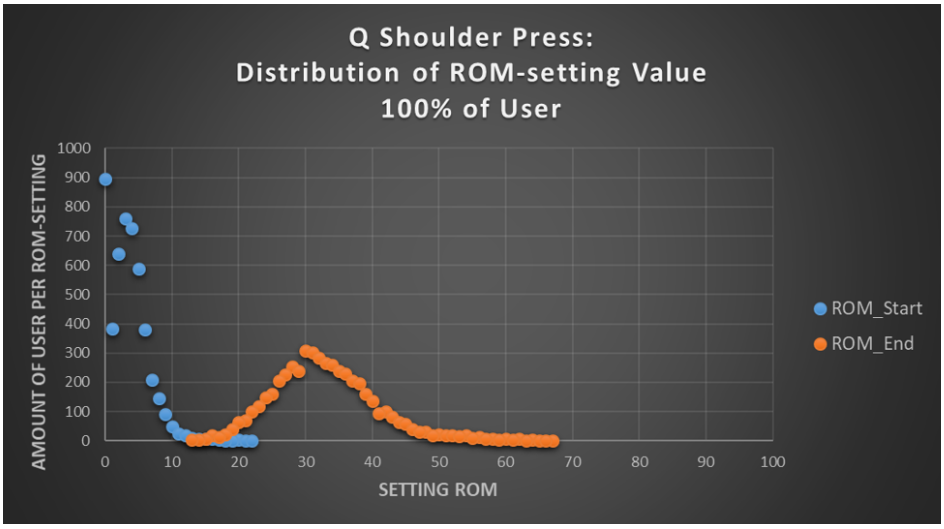

Figure A.8: ROM distribution of Q Shoulder Press[88]

[87]created with Microsoft Excel based on source: milon Care data extraction from 5th March 2019
[88]created with Microsoft Excel based on source: milon Care data extraction from 5th March 2019

Data Analysis Q Leg Press

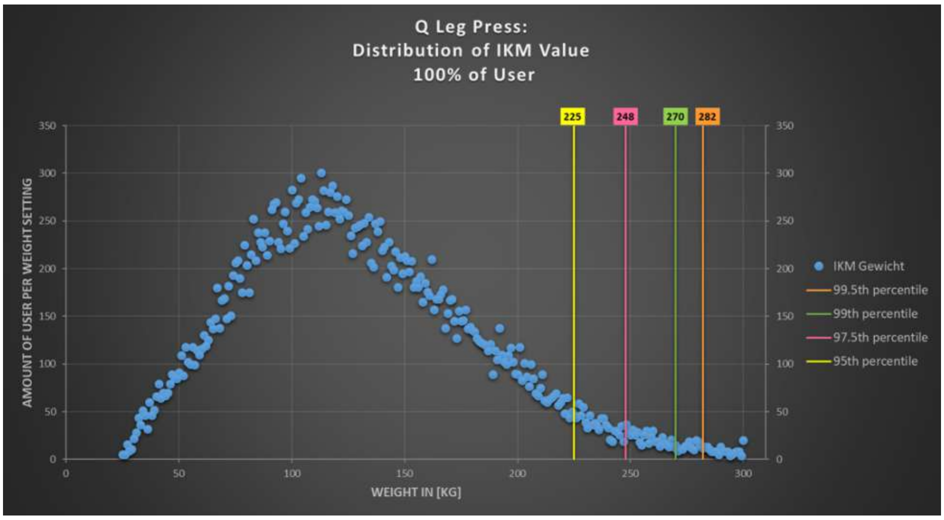

Figure A.9: Maximum strength distribution Q Leg Press[89]

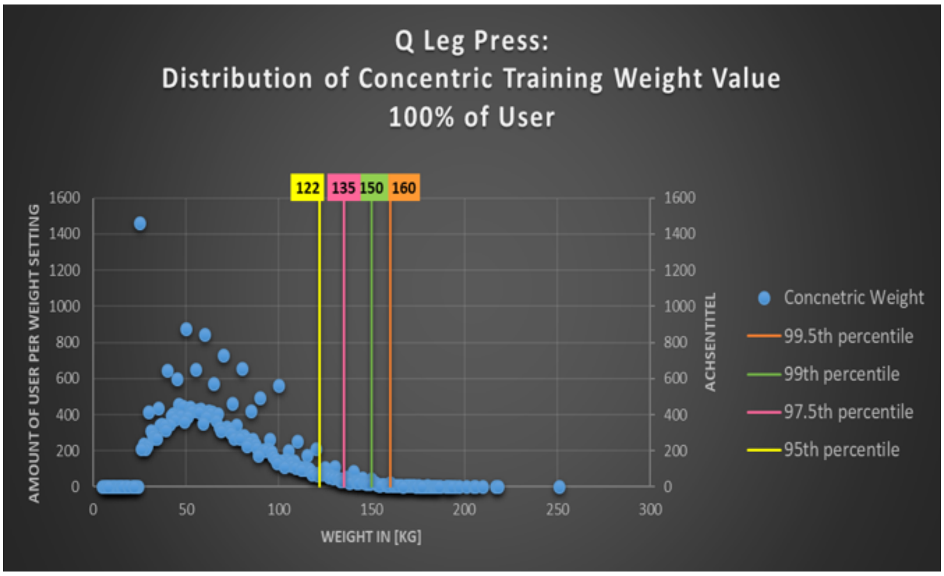

Figure A.10: Concentric training weight distribution Q Leg Press[90]

[89] created with Microsoft Excel based on source: milon Care data extraction from 5th March 2019
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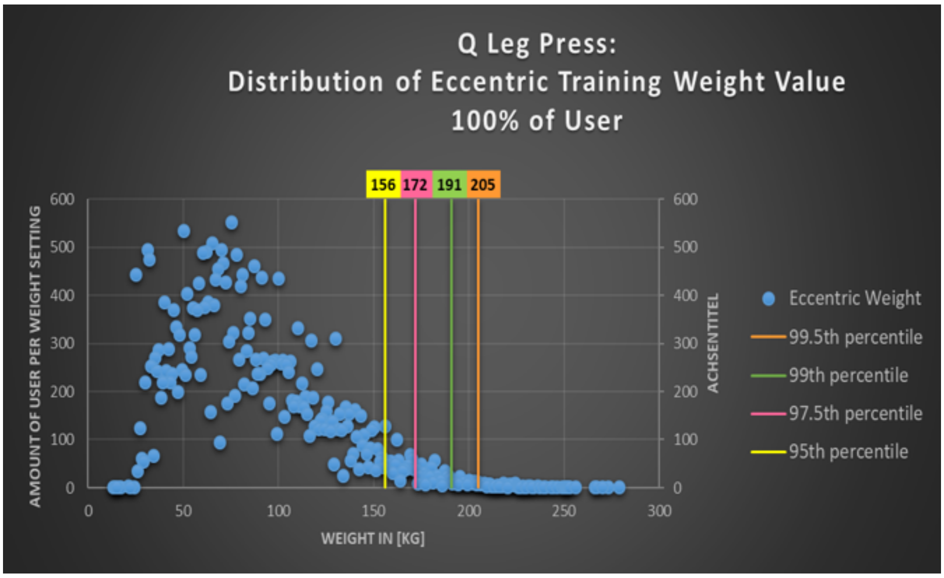

Figure A.11: Eccentric training weight distribution Q Leg Press[91]

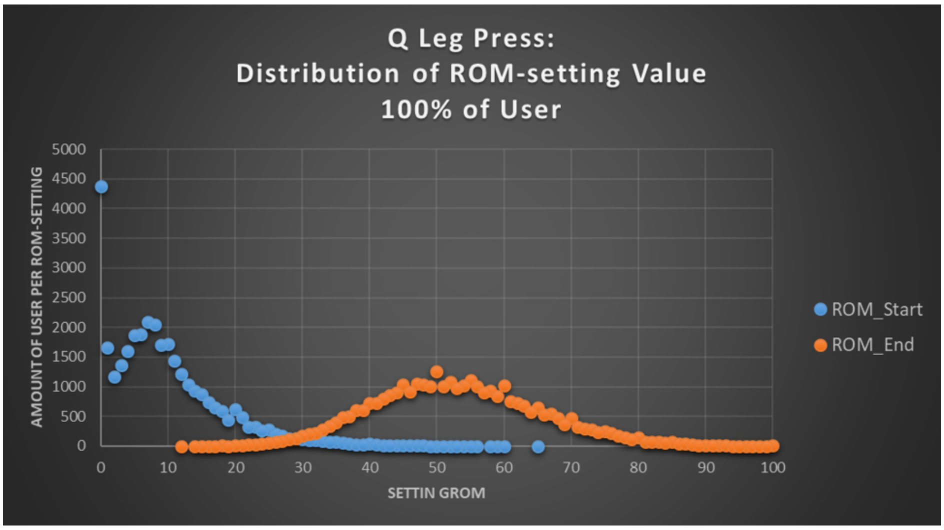

Figure A.12: ROM distribution of Q Leg Press[92]

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Data Analysis Q Biceps Curl

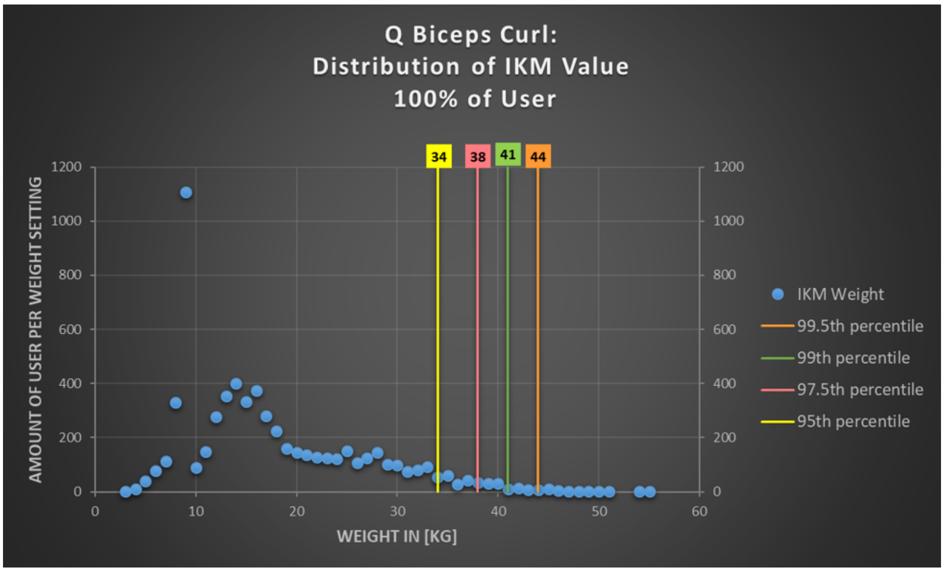

Figure A.13: Maximum strength distribution Q Biceps Curl[93]

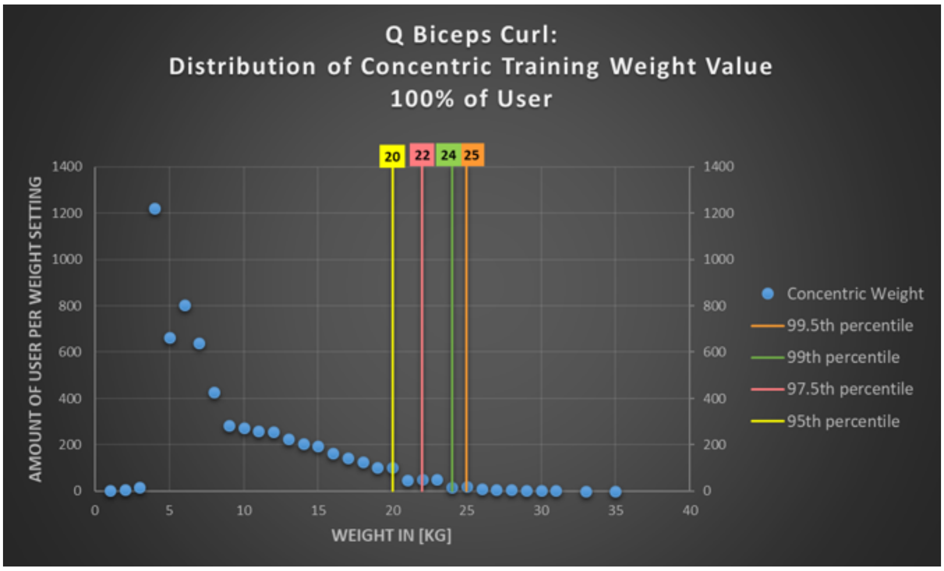

Figure A.14: Concentric training weight distribution Q Biceps Curl[94]

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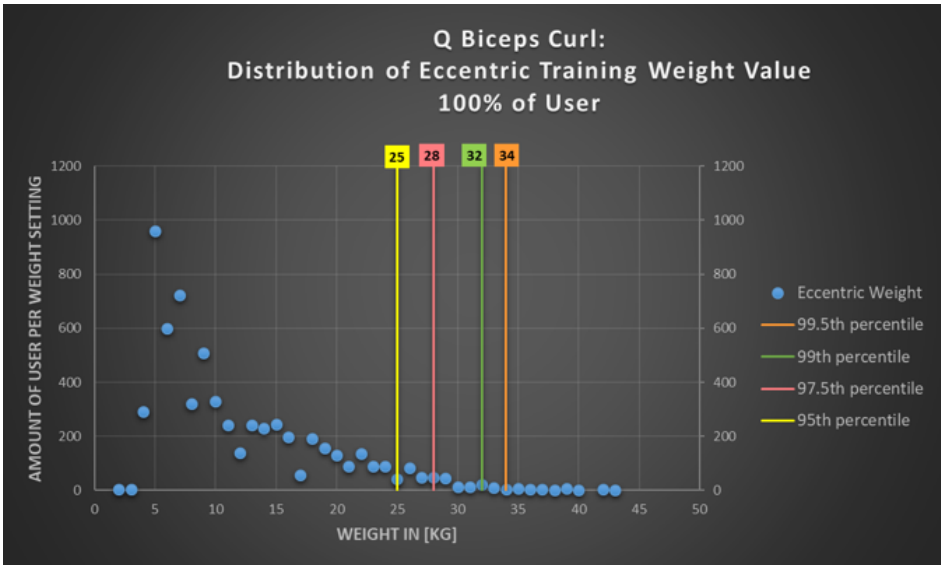

Figure A.15: Eccentric training weight distribution Q Biceps Curl[95]

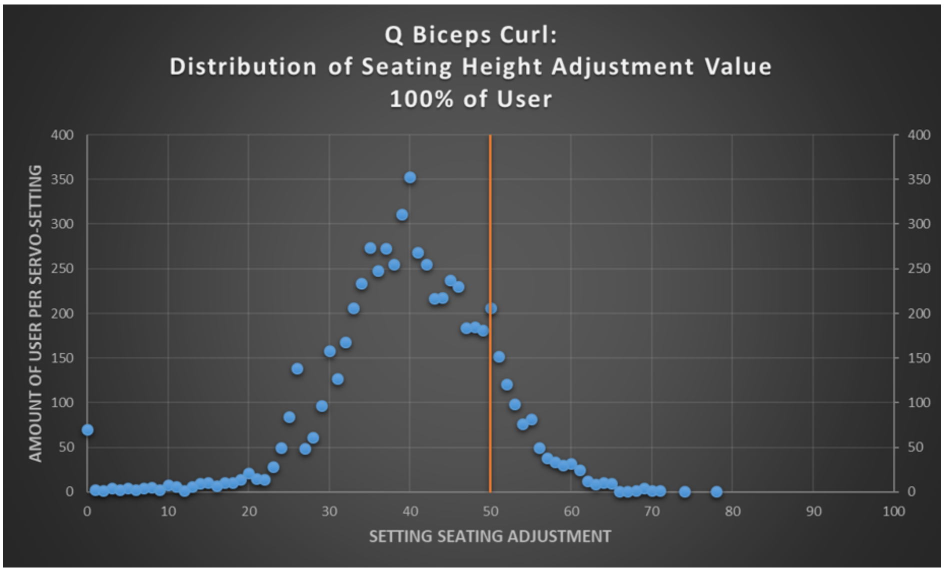

Figure A.16: Seating height adjustment distribution of Q Biceps Curl[96]

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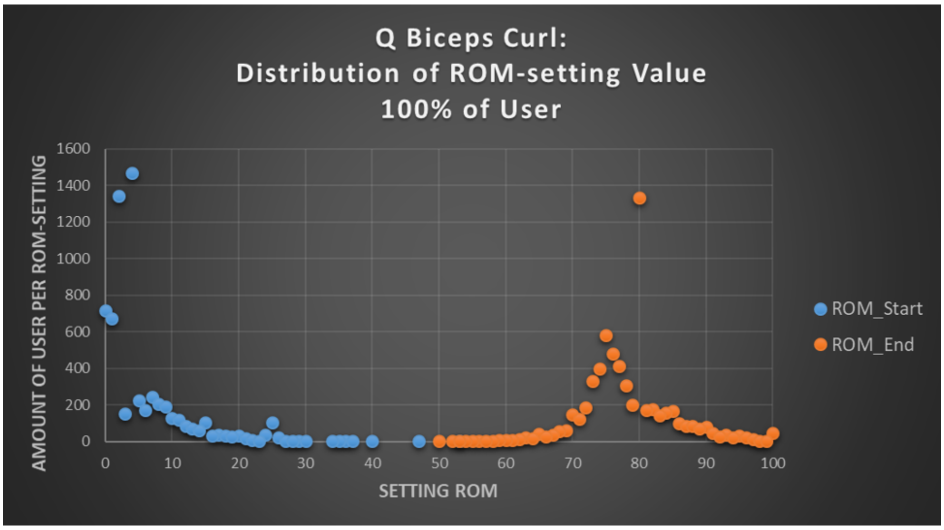

Figure A.17: ROM distribution of Q Biceps Curl[97]

[97]created with Microsoft Excel based on source: milon Care data extraction from 5th March 2019

Data Analysis Q Triceps Extension

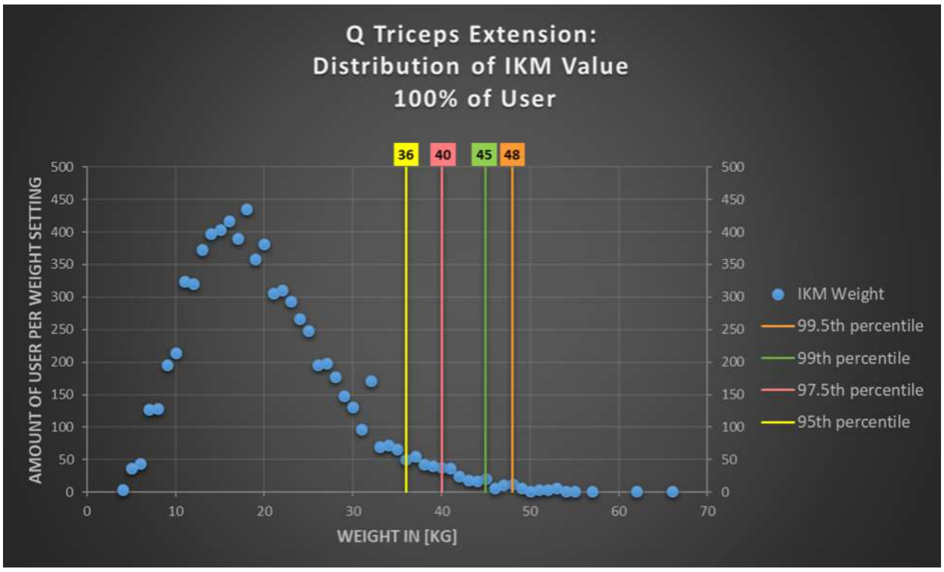

Figure A.18: Maximum strength distribution Q Triceps Extension[98]

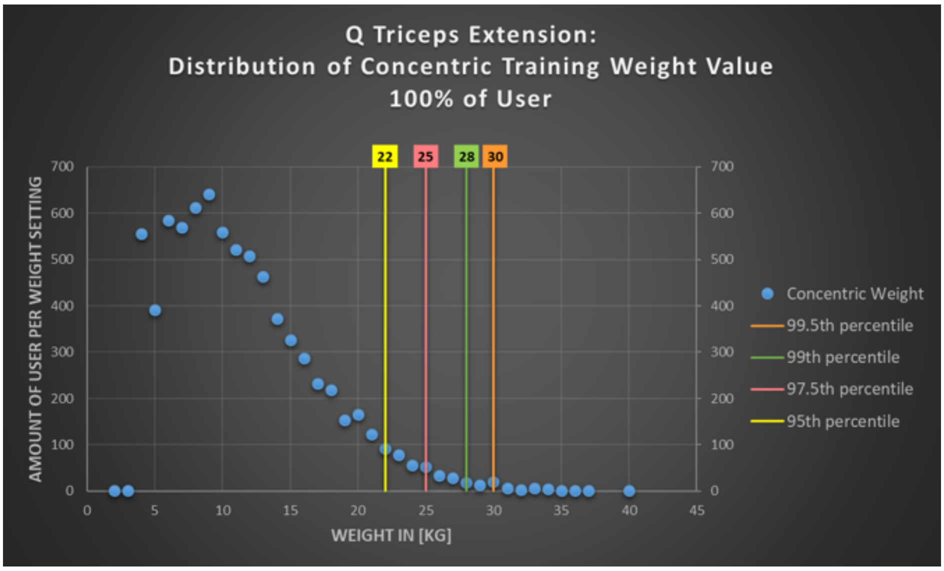

Figure A.19: Concentric training weight distribution Q Triceps Extension[99]

[98]created with Microsoft Excel based on source: milon Care data extraction from 5th March 2019
[99]created with Microsoft Excel based on source: milon Care data extraction from 5th March 2019

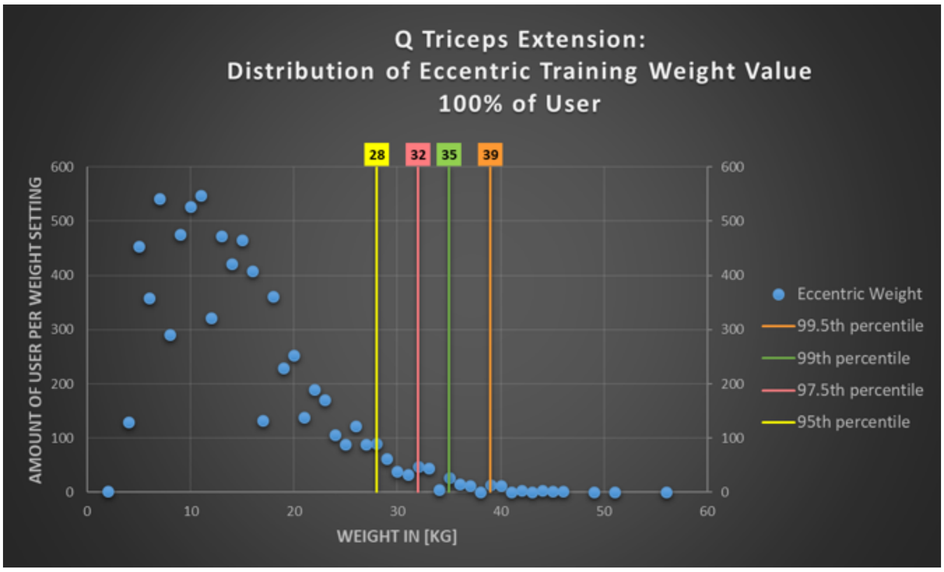

Figure A.20: Eccentric training weight distribution Q Triceps Extension[100]

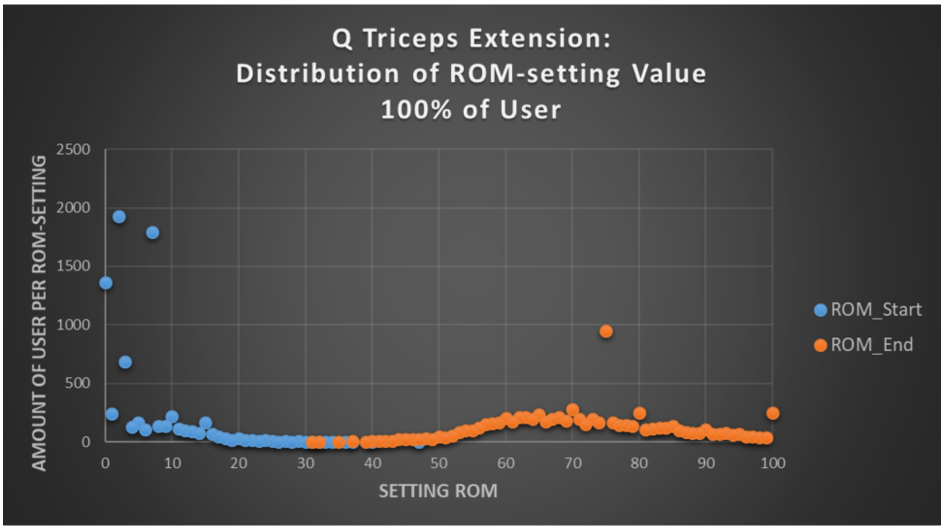

Figure A.21: ROM distribution of Q Triceps Extension[101]

[100] created with Microsoft Excel based on source: milon Care data extraction from 5th March 2019
[101] created with Microsoft Excel based on source: milon Care data extraction from 5th March 2019

A.2. Material cost of generic component groups

Material cost Q Leg Curl

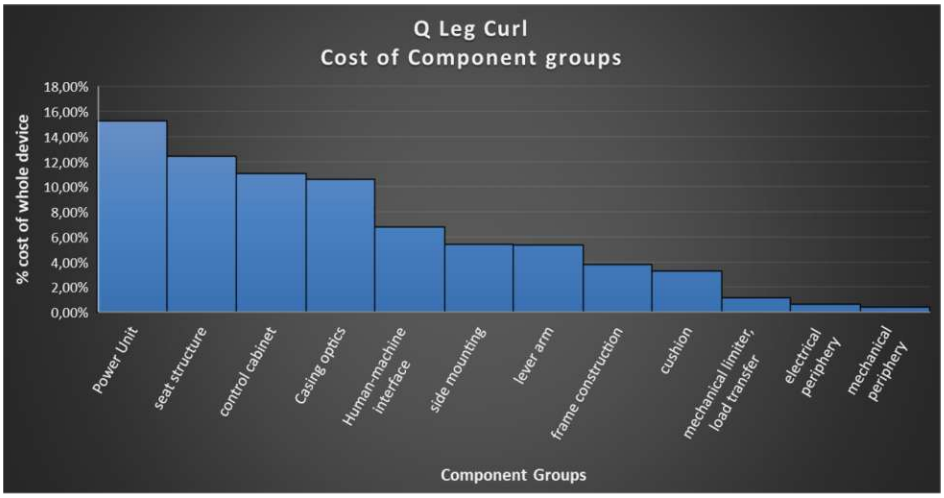

Figure A.22: Component group costs Q Leg Curl[102]

Material cost Q Leg Extension

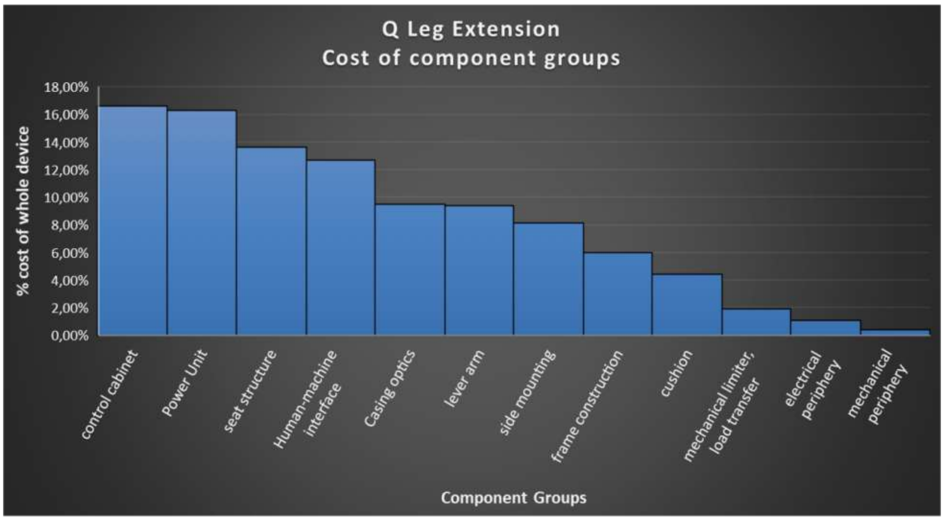

Figure A.23: Component group costs Q Leg Extension[103]

[102]created with Microsoft Excel based on source: material cost extract from ERP-System Abas by purchase department as of 14th March 2019

[103]created with Microsoft Excel based on source: material cost extract from ERP-System Abas by purchase department as of 14th March 2019

Material cost Q Chest Press

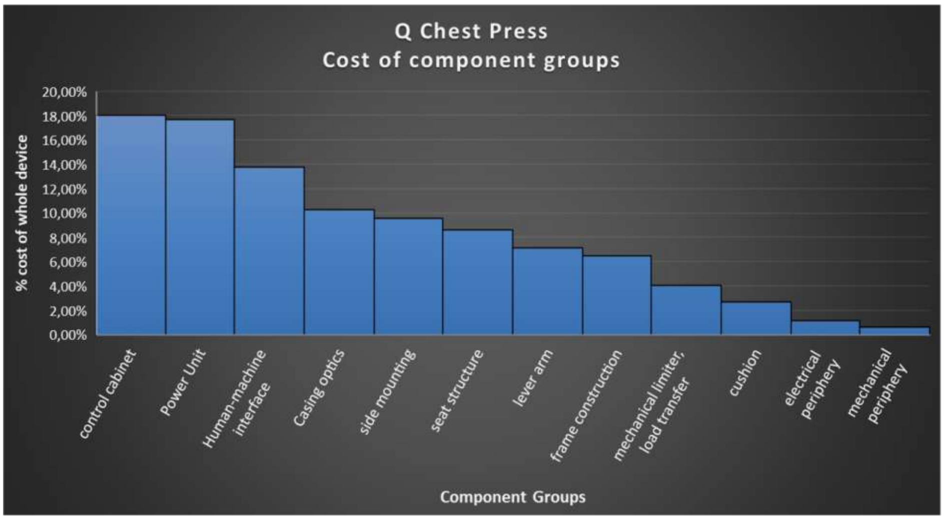

Figure A.24: Component group costs Q Chest Press[104]

Material cost Q Seated Rowing

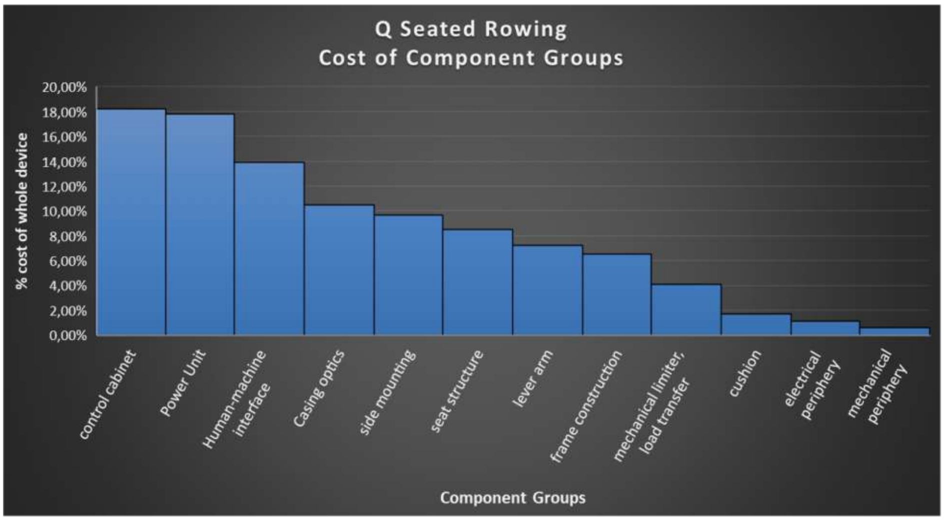

Figure A.25: Component group costs Q Seated Rowing[105]

[104]created with Microsoft Excel based on source: material cost extract from ERP-System Abas by purchase department as of 14th March 2019

[105]created with Microsoft Excel based on source: material cost extract from ERP-System Abas by purchase department as of 14th March 2019

Material cost Q Abdominal Crunch

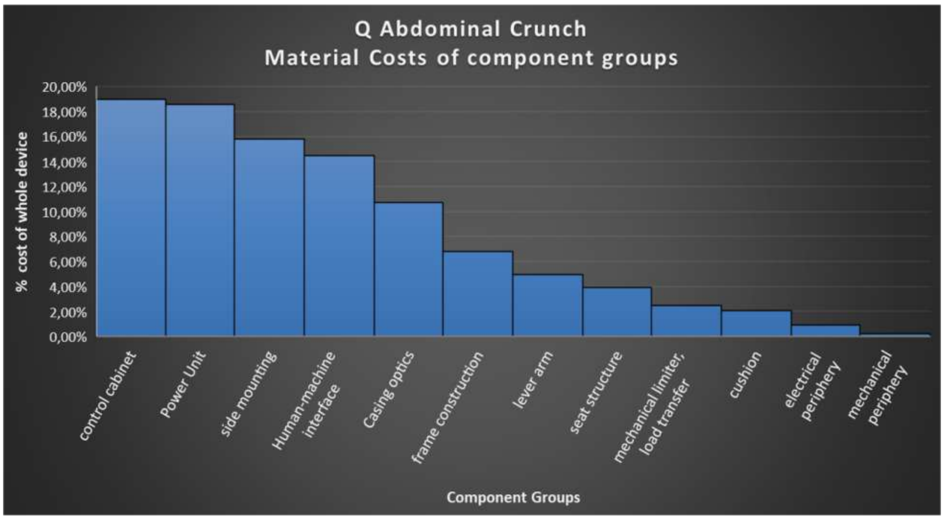

Figure A.26: Component group costs Q Abdominal Crunch[106]

Material cost Q Back Extension

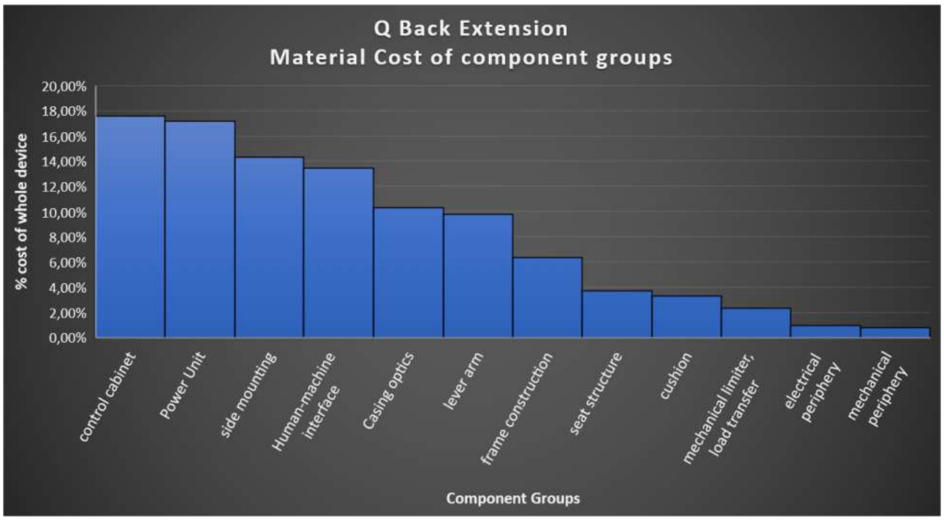

Figure A.27: Component group costs Q Back Extension[107]

[106]created with Microsoft Excel based on source: material cost extract from ERP-System Abas by purchase department as of 14th March 2019

[107]created with Microsoft Excel based on source: material cost extract from ERP-System Abas by purchase department as of 14th March 2019

A.3. Function cost matrix

Function cost matrix Q Leg Extension

Q Leg Extension	Providing trainings resistance	Ensuring User security	Electronic control	Ensuring usability	Ensuring user's physiological training position	Structural safety of machine	Assistance for User	Excercise feedback	Aesthetic product design	sum function of component group	atual component group costs [MC]	actual % of component group costs	target component cost from paired comparison [MC]	target % of component cost from paired comparison	delta target-actual cost [MC]	delta target-actual in %
Power Unit	2	0	0	0	0	0	0	1	0	3	7637,89	16,27%	2874,04	6,12%	-4763,85	-62,37%
Casing optics	0	1	0	0	0	0	0	0	2	3	4464,53	9,51%	2874,04	6,12%	-1590,50	-35,63%
Human-machine-interface	0	0	2	2	1	0	0	2	2	9	5964,60	12,71%	8622,12	18,37%	2657,52	44,55%
lever arm	2	0	0	1	2	0	0	0	1	6	4415,19	9,41%	5748,08	12,24%	1332,89	30,19%
mechanical limiter, load transfer	2	2	0	0	0	0	0	0	0	4	899,72	1,92%	3832,05	8,16%	2932,33	325,91%
cushion	0	1	0	1	1	0	0	0	2	5	2073,84	4,42%	4790,07	10,20%	2716,22	130,98%
frame	0	0	0	0	0	2	0	0	1	3	2803,91	5,97%	2874,04	6,12%	70,13	2,50%
control cabinet	1	0	2	0	1	0	0	1	0	5	7800,06	16,62%	4790,07	10,20%	-3009,99	-38,59%
side mounting	0	0	0	0	0	2	0	0	1	3	3822,36	8,14%	2874,04	6,12%	-948,32	-24,81%
seat structure	0	0	0	1	2	1	1	0	1	6	6389,43	13,61%	5748,08	12,24%	-641,35	-10,04%
electrical periphery	0	0	1	0	0	0	0	0	0	1	498,89	1,06%	958,01	2,04%	459,12	92,03%
mechanical periphery	0	0	0	0	0	1	0	0	0	1	172,22	0,37%	958,01	2,04%	785,79	456,28%
sum of function	7	4	5	5	7	6	1	4	10							
actual function costs [MC]	6706,09	3832,05	4790,07	4790,07	6706,09	5748,08	958,01	3832,05	9580,13							
actual % of function cost	14,29%	8,16%	10,20%	10,20%	14,29%	12,24%	2,04%	8,16%	20,41%							
sum of weighted function	16	20	11	14	16	20	5	7	12							
% of weighted function	13,22%	16,53%	9,09%	11,57%	13,22%	16,53%	4,13%	5,79%	9,92%							
target function cost from paired comparison [MC]	6207,29	7759,11	4267,51	5431,38	6207,29	7759,11	1939,78	2715,69	4655,47							
delta target-actual cost [MC]	-498,80	3927,06	-522,55	641,31	-498,80	2011,04	981,77	-1116,36	-4924,66							
delta target-actual in %	-7,44%	102,48%	-10,91%	13,39%	-7,44%	34,99%	102,48%	-29,13%	-51,40%							

Legend		
2	1	0
main function	secondary funciton	no function

Figure A.28: Function cost matrix for Q Leg Extension[108]

[108] created with Microsoft Excel as of 24th April 2019

Function cost matrix Q Chest Press

Q Chest Press (Component Groups / Function groups)	Providing trainings resistance	Ensuring User security	Electronic control	Ensuring usability	Ensuring user's physiological training position	Structural safety of machine	Assistance for User	Exercise feedback	Aesthetic product design	sum function of component group	atual component group costs [MC]	actual % of component group costs	target component cost from paired comparison [MC]	target % of component cost from paired comparison	delta target-actual cost [MC]	delta target-actual in %
Power Unit	2	0	0	0	0	0	0	1	0	3	7637,89	17,64%	2763,98	6,38%	-4873,90	-63,81%
Casing optics	0	1	0	0	0	0	0	0	2	3	4458,43	10,30%	2763,98	6,38%	-1694,45	-38,01%
Human-machine-interface	0	0	2	2	1	0	0	2	2	9	5964,60	13,77%	8291,94	19,15%	2327,34	39,02%
lever arm	2	0	0	1	2	0	0	0	1	6	3096,14	7,15%	5527,96	12,77%	2431,82	78,54%
mechanical limiter, load transfer	2	2	0	0	0	0	0	0	0	4	1764,88	4,08%	3685,31	8,51%	1920,43	108,81%
cushion	0	0	0	1	1	0	0	0	2	4	1165,61	2,69%	3685,31	8,51%	2519,70	216,17%
frame	0	0	0	0	0	2	0	0	1	3	2801,91	6,47%	2763,98	6,38%	-37,93	-1,35%
control cabinet	1	0	2	0	1	0	0	1	0	5	7800,06	18,01%	4606,63	10,64%	-3193,42	-40,94%
side mounting	0	0	0	0	0	2	0	0	1	3	4133,92	9,55%	2763,98	6,38%	-1369,93	-33,14%
seat structure	0	0	0	1	2	1	0	0	1	5	3719,21	8,59%	4606,63	10,64%	887,42	23,86%
electrical periphery	0	0	1	0	0	0	0	0	0	1	489,80	1,13%	921,33	2,13%	431,53	88,10%
mechanical periphery	0	0	0	0	0	1	0	0	0	1	269,94	0,62%	921,33	2,13%	651,39	241,31%
sum of function	7	3	5	5	7	6	0	4	10							
actual function costs [MC]	6449,29	2763,98	4606,63	4606,63	6449,29	5527,96	0,00	3685,31	9213,27							
actual % of function cost	14,89%	6,38%	10,64%	10,64%	14,89%	12,77%	0,00%	8,51%	21,28%							
sum of weighted function	16	19	11	14	16	20	4	7	12							
% of weighted function	13,45%	15,97%	9,24%	11,76%	13,45%	16,81%	3,36%	5,88%	10,08%							
target function cost from paired comparison [MC]	5822,17	6913,82	4002,74	5094,40	5822,17	7277,71	1455,54	2547,20	4366,63							
delta target-actual cost [MC]	-627,12	4149,84	-603,89	487,76	-627,12	1749,75	1455,54	-1138,11	-4846,64							
delta target-actual in %	-9,72%	150,14%	-13,11%	10,59%	-9,72%	31,65%	#DIV/0!	-30,88%	-52,61%							

Legend		
2	1	0
main function	secondary funciton	no function

Figure A.29: Function cost matrix for Q Chest Press[109]

[109]created with Microsoft Excel as of 24th April 2019

Function cost matrix Q Seated Rowing

	Function groups															
Q Seated Rowing	Providing trainings resistance	Ensuring User security	Electronic control	Ensuring usability	Ensuring user's physiological training position	Structural safety of machine	Assistance for User	Excercise feedback	Aesthetic product design	sum function of component group	atual component group costs [MC]	actual % of component group costs	target component cost from paired comparison [MC]	target % of component cost from paired comparison	delta target-actual cost [MC]	delta target-actual in %
Component Groups																
Power Unit	2	0	0	0	0	0	0	1	0	3	7637,89	17,82%	2735,17	6,55%	-4902,71	-64,19%
Casing optics	0	1	0	0	0	0	0	0	2	3	4498,40	10,50%	2735,17	6,55%	-1763,23	-39,20%
Human-machine-interface	0	0	2	2	1	0	0	2	2	9	5964,60	13,92%	8205,51	19,64%	2240,92	37,57%
lever arm	2	0	0	1	2	0	0	0	1	6	3097,31	7,23%	5470,34	13,10%	2373,03	76,62%
mechanical limiter, load transfer	2	2	0	0	0	0	0	0	0	4	1764,88	4,12%	3646,90	8,73%	1882,02	106,64%
cushion	0	0	0	1	1	0	0	0	2	4	735,03	1,72%	3646,90	8,73%	2911,87	396,16%
frame	0	0	0	0	0	2	0	0	1	3	2803,91	6,54%	2735,17	6,55%	-68,73	-2,45%
control cabinet	1	0	2	0	1	0	0	1	0	5	7800,06	18,20%	4558,62	10,91%	-3241,44	-41,56%
side mounting	0	0	0	0	0	2	0	0	1	3	4147,35	9,68%	2735,17	6,55%	-1412,18	-34,05%
seat structure	0	0	0	1	2	1	0	0	1	5	3658,75	8,54%	4558,62	10,91%	899,87	24,60%
electrical periphery	0	0	1	0	0	0	0	0	0	1	489,80	1,14%	489,80	1,17%	0,00	0,00%
mechanical periphery	0	0	0	0	0	1	0	0	0	1	253,07	0,59%	253,07	0,61%	0,00	0,00%
sum of function	7	3	5	5	7	6	0	4	10							
actual function costs [MC]	6382,07	2735,17	4558,62	4558,62	6382,07	5470,34	0,00	3646,90	9117,24							
actual % of function cost	14,89%	6,38%	10,64%	10,64%	14,89%	12,77%	0,00%	8,51%	21,28%							
sum of weighted function	16	19	11	14	16	20	4	7	12							
% of weighted function	13,45%	15,97%	9,24%	11,76%	13,45%	16,81%	3,36%	5,88%	10,08%							
target function cost from paired comparison [MC]	5761,48	6841,76	3961,02	5041,30	5761,48	7201,85	1440,37	2520,65	4321,11							
delta target-actual cost [MC]	-620,59	4106,59	-597,60	482,68	-620,59	1731,51	1440,37	-1126,25	-4796,13							
delta target-actual in %	-9,72%	150,14%	-13,11%	10,59%	-9,72%	31,65%	#DIV/0!	-30,88%	-52,61%							

Legend		
2	1	0
Hauptfunktion	Nebenfunktion	keine Funktion

Figure A.30: Function cost matrix for Q Seated Rowing[110]

[110]created with Microsoft Excel as of 24th April 2019

Function cost matrix Q Abdominal Crunch

Q Abdominal Crunch	Providing trainings resistance	Ensuring User security	Electronic control	Ensuring usability	Ensuring user's physiological training position	Structural safety of machine	Assistance for User	Excercise feedback	Aesthetic product design	sum function of component group	atual component group costs [MC]	actual % of component group costs	target component cost from paired comparison [MC]	target % of component cost from paired comparison	delta target-actual cost [MC]	delta target-actual in %
Power Unit	2	0	0	0	0	0	0	1	0	3	7637,89	18,57%	2467,33	6,00%	-5170,55	-67,70%
Casing optics	0	1	0	0	0	0	0	0	2	3	4412,24	10,73%	2467,33	6,00%	-1944,91	-44,08%
Human-machine-interface	0	0	2	2	1	0	0	2	2	9	5964,60	14,50%	7402,00	18,00%	1437,40	24,10%
lever arm	2	0	0	1	2	0	0	0	1	6	2029,96	4,94%	4934,66	12,00%	2904,70	143,09%
mechanical limiter, load transfer	2	2	0	0	0	0	0	0	0	4	1030,19	2,51%	3289,78	8,00%	2259,59	219,34%
cushion	0	0	0	1	1	0	0	0	2	4	847,95	2,06%	3289,78	8,00%	2441,83	287,97%
frame	0	0	0	0	0	2	0	0	1	3	2803,91	6,82%	2467,33	6,00%	-336,57	-12,00%
control cabinet	1	0	2	0	1	0	0	1	0	5	7800,06	18,97%	4112,22	10,00%	-3687,84	-47,28%
side mounting	0	0	0	1	1	2	1	0	1	6	6494,42	15,79%	4934,66	12,00%	-1559,76	-24,02%
seat structure	0	0	0	1	2	1	0	0	1	5	1609,84	3,91%	4112,22	10,00%	2502,38	155,44%
electrical periphery	0	0	1	0	0	0	0	0	0	1	385,14	0,94%	822,44	2,00%	437,31	113,55%
mechanical periphery	0	0	0	0	0	1	0	0	0	1	106,03	0,26%	822,44	2,00%	716,42	675,68%
sum of function	7	3	5	6	8	6	1	4	10							
actual function costs [MC]	5757,11	2467,33	4112,22	4934,66	6579,55	4934,66	822,44	3289,78	8224,44							
actual % of function cost	14,00%	6,00%	10,00%	12,00%	16,00%	12,00%	2,00%	8,00%	20,00%							
sum of weighted function	16	19	11	15	17	20	5	7	12							
% of weighted function	13,11%	15,57%	9,02%	12,30%	13,93%	16,39%	4,10%	5,74%	9,84%							
target function cost from paired comparison [MC]	5393,08	6404,28	3707,74	5056,01	5730,14	6741,35	1685,34	2359,47	4044,81							
delta target-actual cost [MC]	-364,03	3936,95	-404,48	121,34	-849,41	1806,68	862,89	-930,31	-4179,63							
delta target-actual in %	-6,32%	159,56%	-9,84%	2,46%	-12,91%	36,61%	104,92%	-28,28%	-50,82%							

Function groups / Component groups

Legend		
2	1	0
main function	secondary funciton	no function

Figure A.31: Function cost matrix for Q Abdominal Crunch[111]

[111] created with Microsoft Excel as of 24th April 2019

Function cost matrix Q Back Extension

Q Back Extension (Component groups / Function groups)	Providing trainings resistance	Ensuring User security	Electronic control	Ensuring usability	Ensuring user's physiological training position	Structural safety of machine	Assistance for User	Excercise feedback	Aesthetic product design	sum function of component group	atual component group costs [MC]	actual % of component group costs	target component cost from paired comparison [MC]	target % of component cost from paired comparison	delta target-actual cost [MC]	delta target-actual in %
Power Unit	2	0	0	0	0	0	0	1	0	3	7637,89	17,22%	2609,59	5,88%	-5028,30	-65,83%
Casing optics	0	1	0	0	0	0	0	0	2	3	4427,45	9,98%	2609,59	5,88%	-1817,86	-41,06%
Human-machine-interface	0	0	2	2	1	0	0	2	2	9	5964,60	13,44%	7828,76	17,65%	1864,17	31,25%
lever arm	2	0	0	1	2	0	0	0	1	6	4546,95	10,25%	5219,18	11,76%	672,22	14,78%
mechanical limiter, load transfer	2	2	0	0	0	0	0	0	0	4	899,72	2,03%	3479,45	7,84%	2579,73	286,72%
cushion	0	1	0	1	1	0	0	0	2	5	1455,84	3,28%	4349,31	9,80%	2893,47	198,75%
frame	0	0	0	0	0	2	0	0	1	3	2803,91	6,32%	2609,59	5,88%	-194,32	-6,93%
control cabinet	1	0	2	0	1	0	0	1	0	5	7800,06	17,58%	4349,31	9,80%	-3450,74	-44,24%
side mounting	0	0	0	1	1	2	1	0	1	6	6475,24	14,60%	5219,18	11,76%	-1256,06	-19,40%
seat structure	0	0	0	1	2	1	0	0	1	5	1640,82	3,70%	4349,31	9,80%	2708,49	165,07%
electrical periphery	0	0	1	0	0	0	0	0	0	1	427,54	0,96%	869,86	1,96%	442,32	103,46%
mechanical periphery	0	0	0	0	0	1	0	0	0	1	282,99	0,64%	869,86	1,96%	586,88	207,39%
sum of function	7	4	5	6	8	6	1	4	10							
actual function costs [MC]	6089,04	3479,45	4349,31	5219,18	6958,90	5219,18	869,86	3479,45	8698,63							
actual % of function cost	13,73%	7,84%	9,80%	11,76%	15,69%	11,76%	1,96%	7,84%	19,61%							
sum of weighted function	16	20	11	15	17	20	5	7	12							
% of weighted function	13,01%	16,26%	8,94%	12,20%	13,82%	16,26%	4,07%	5,69%	9,76%							
target function cost from paired comparison [MC]	5770,80	7213,50	3967,42	5410,12	6131,47	7213,50	1803,37	2524,72	4328,10							
delta target-actual cost [MC]	-318,24	3734,04	-381,89	190,95	-827,43	1994,32	933,51	-954,73	-4370,53							
delta target-actual in %	-5,23%	107,32%	-8,78%	3,66%	-11,89%	38,21%	107,32%	-27,44%	-50,24%							

Legend		
2	1	0
main function	secondary funciton	no function

Figure A.32: Function cost matrix for Q Back Extension[112]

[112] created with Microsoft Excel as of 24th April 2019

A.4. Comparison actual and target costs

Actual and target cost comparison Q Leg Extension

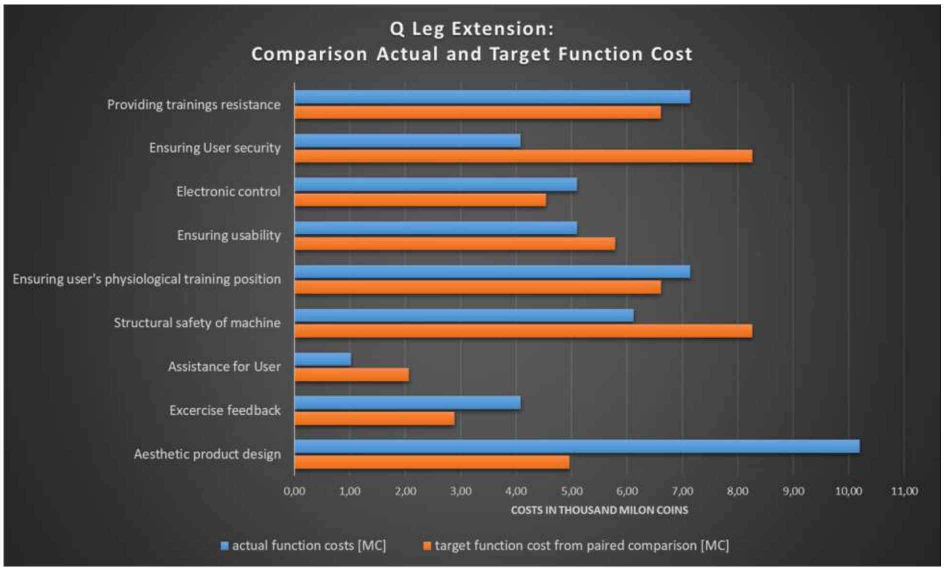

Figure A.33: Actual and target function cost Q Leg Extension[113]

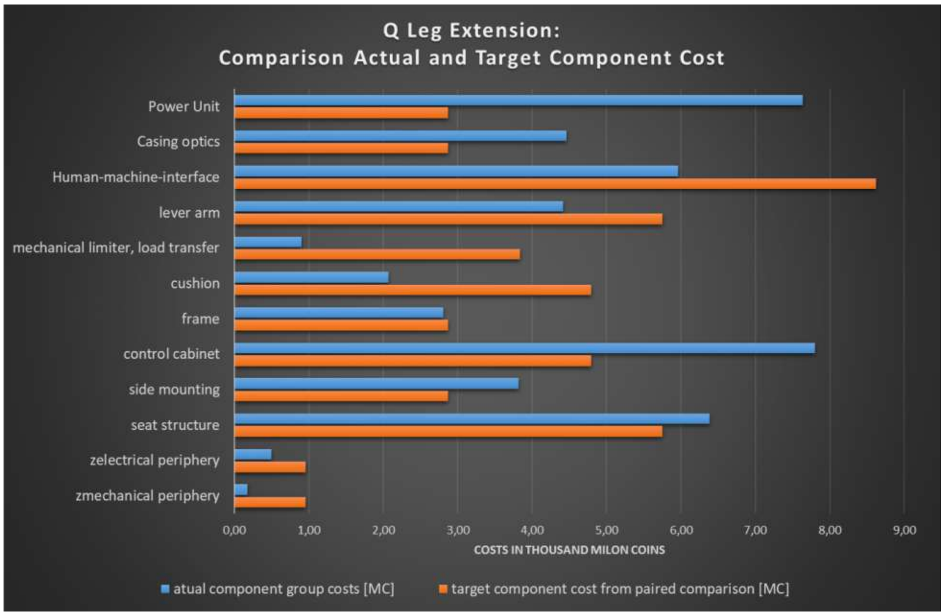

Figure A.34: Actual and target component group cost Q Leg Extension[114]

[113] created with Microsoft Excel as of 25th May 2019
[114] created with Microsoft Excel as of 25th May 2019

Actual and target cost comparison Q Chest Press

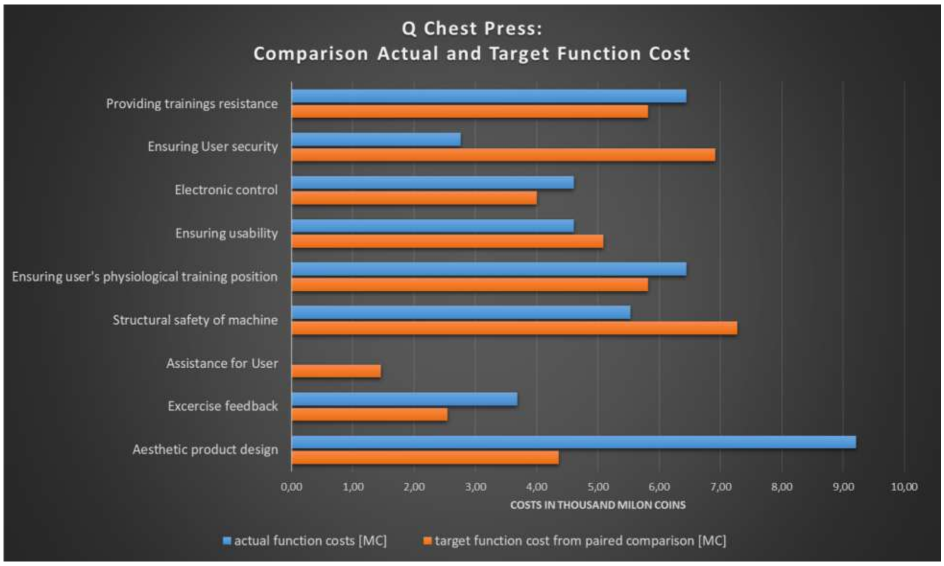

Figure A.35: Actual and target function cost Q Chest Press[115]

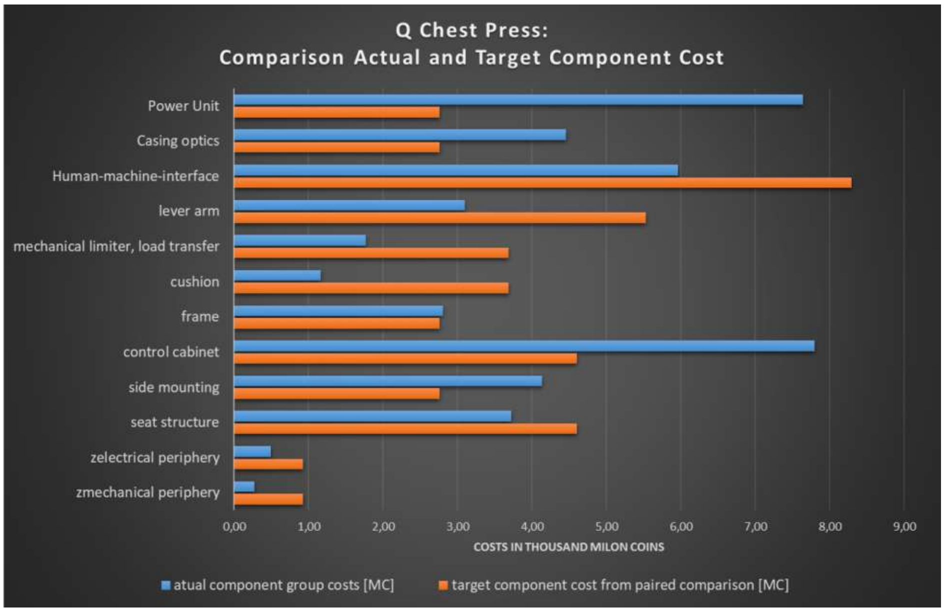

Figure A.36: Actual and target component group cost Q Chest Press[116]

115 created with Microsoft Excel as of 25th May 2019
116 created with Microsoft Excel as of 25th May 2019

Actual and target cost comparison Q Seated Rowing

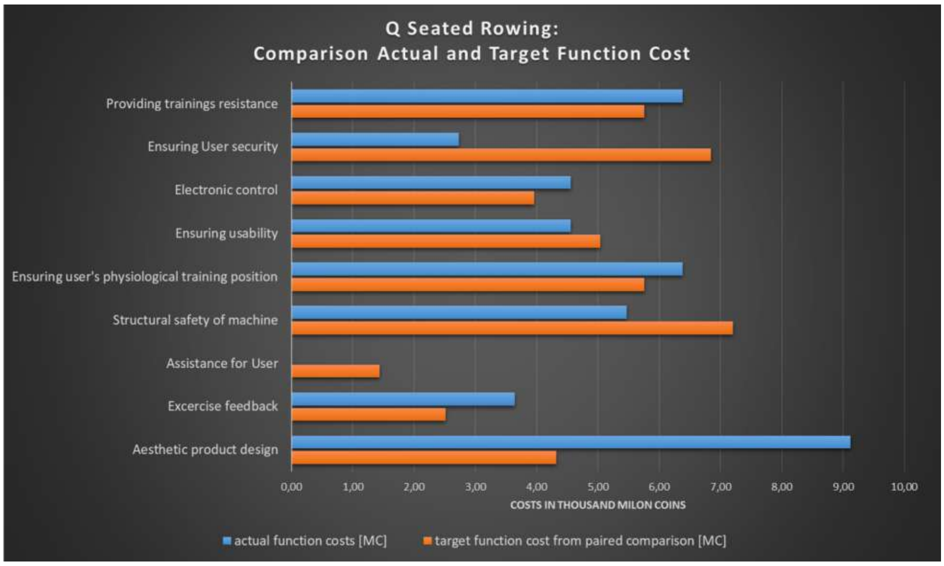

Figure A.37: Actual and target function cost Q Seated Rowing[117]

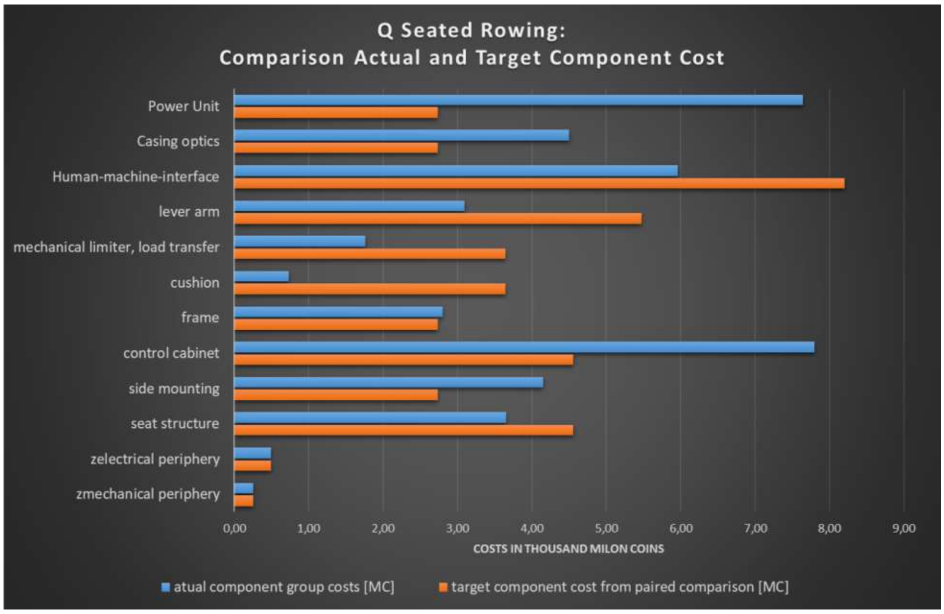

Figure A.38: Actual and target component group cost Q Seated Rowing[118]

[117] created with Microsoft Excel as of 25th May 2019
[118] created with Microsoft Excel as of 25th May 2019

Actual and target cost comparison Q Abdominal Crunch

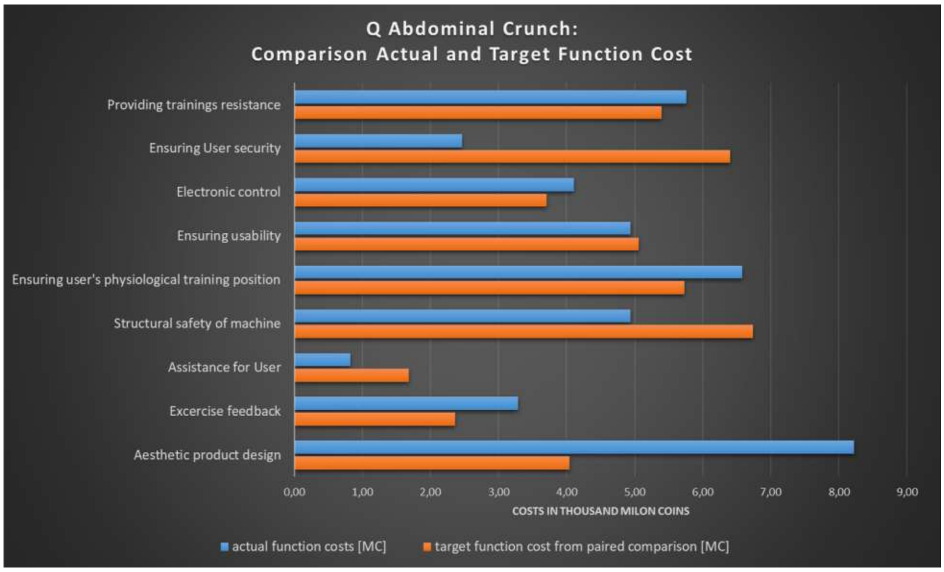

Figure A.39: Actual and target function cost Q Abdominal Crunch[119]

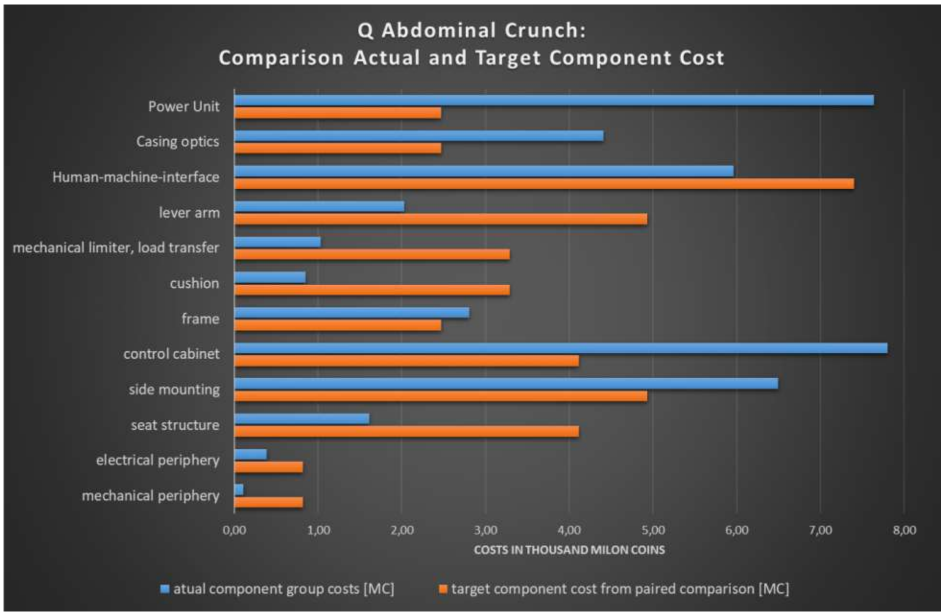

Figure A.40: Actual and target component group cost Q Abdominal Crunch[120]

[119]created with Microsoft Excel as of 25th May 2019
[120]created with Microsoft Excel as of 25th May 2019

Actual and target cost comparison Q Back Extension

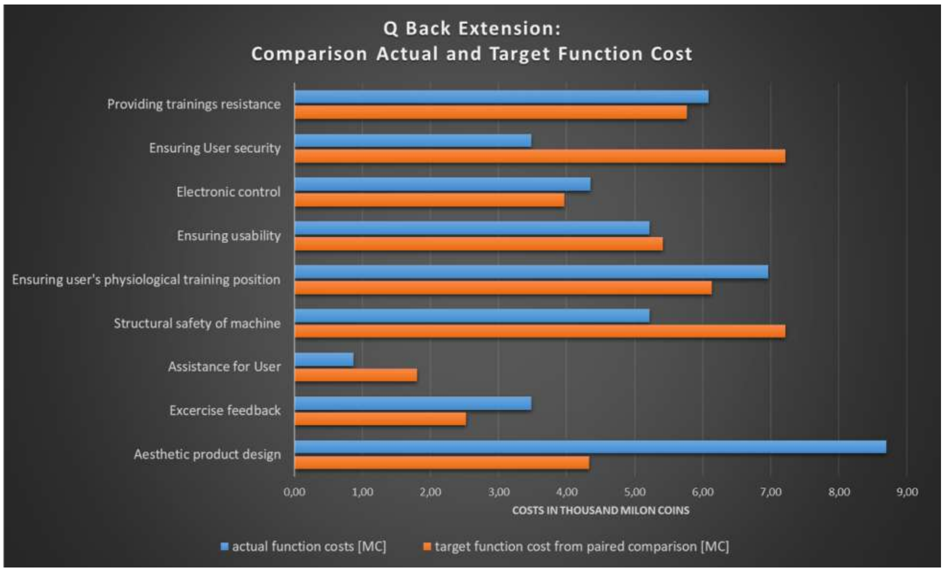

Figure A.41: Actual and target function cost Q Back Extension[121]

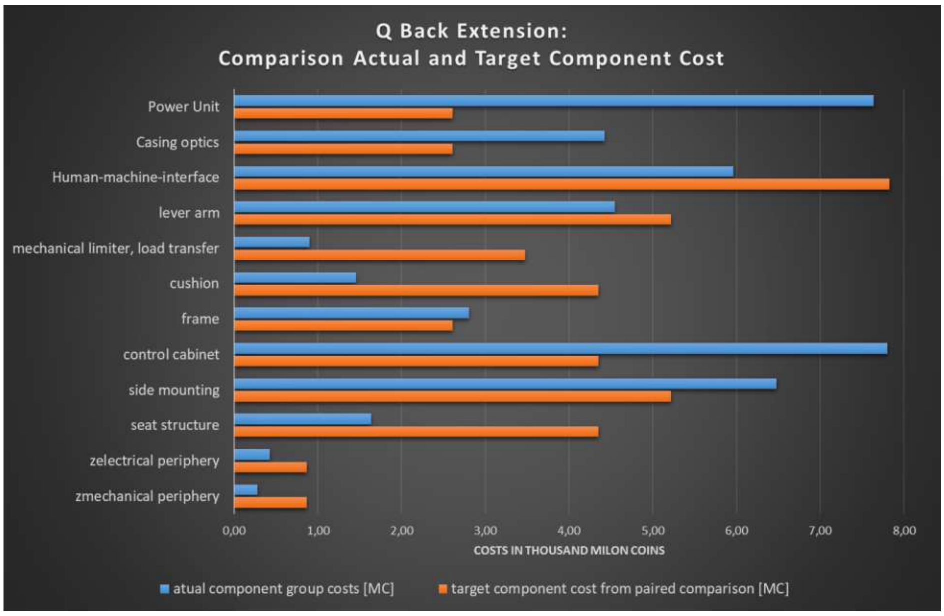

Figure A.42: Actual and target component group cost Q Back Extension[122]

[121]created with Microsoft Excel as of 25th May 2019
[122]created with Microsoft Excel as of 25th May 2019

A.5. Cost estimate of strength training machines

Cost estimate Leg Curl concepts

Q Leg Curl					
Measure	Grade	Component	Change with respect to Q	Potential	Unit
1	HG1	Side mounting	welded rectangular profile with PA66 cover, without inlay cover	-2.331,66	MC/Machine
2	HG1	Optics: Side mounting, seat structure, lever arm	change powder coating material to tiger drylac RAL9005	-144,34	MC/Machine
3	HG1	Casing	casing material standard ABS without PMMA foil	[redacted]	MC/Machine
4	HG1	Display holder	display connection rectangular profile without casing	none	MC/Machine
5	HG1	Lever arm	no auxiliary drive, locking bolt and disc	-980,96	MC/Machine
7	HG2	Optics	change grip caps material to ABS	[redacted]	MC/Machine
8	HG2	Optics	change grip rings material to ABS	[redacted]	MC/Machine
9	HG2	Cushion	change coating material to artificial leather	-233,17	MC/Machine
10	HG3	Cushion	round cushion lever arm	-63,95	MC/Machine
11	HG3	Power unit	change to bevel geared motor from batch 3	[redacted]	MC/Machine
12	HG3	Tray	tray from milonizer	-65,51	MC/Machine
13	HG3	HMI	no pulse receiver	[redacted]	MC/Machine

Figure A.43: Cost estimate for the concepts of the Leg Curl[123]

Cost estimate Leg Extension concepts

Q Leg Extension					
Measure	Grade	Component	Change with respect to Q	Potential	Unit
1	HG1	Side mounting	welded rectangular profile with PA66 cover, without inlay cover	-2.331,66	MC/Machine
2	HG1	Optics: Side mounting, set structure, lever arm	change powder coating material to tiger drylac RAL9005	-144,34	MC/Machine
3	HG1	Casing	casing material standard ABS without PMMA foil	[redacted]	MC/Machine
4	HG1	Display holder	display connection rectangular profile without casing	none	MC/Machine
5	HG1	Lever arm	no auxiliary drive, locking bolt and disc	-980,96	MC/Machine
7	HG2	Optics	change grip caps material to ABS	[redacted]	MC/Machine
9	HG2	Cushion	change coating material to artificial leather	-177,65	MC/Machine
10	HG3	Cushion	round cushion lever arm	-63,95	MC/Machine
11	HG3	Power unit	change to bevel geared motor from batch 3	[redacted]	MC/Machine
12	HG3	Tray	tray from milonizer	-65,51	MC/Machine
13	HG3	HMI	no pulse receiver	[redacted]	MC/Machine

Figure A.44: Cost estimate for the concepts of the Leg Extension[124]

[123] created with Microsoft Excel as of 12th June 2019
[124] created with Microsoft Excel as of 12th June 2019

Cost estimate Chest Press concepts

Q Chest Press					
Measure	Grade	Component	Change with respect to Q	Potential	Unit
1	HG1	Side mounting, seat structure	welded rectangular profile with PA66 cover, without inlay cover, no lifting column	-5.629,40	MC/Machine
2	HG1	Optics: Side mounting, set structure, lever arm	change powder coating material to tiger drylac RAL9005	-144,34	MC/Machine
3	HG1	Casing	casing material standard ABS without PMMA foil	[redacted]	MC/Machine
4	HG1	Display holder	display connection rectangular profile without casing	none	MC/Machine
5	HG1	Lever arm	two bent grips	333,09	MC/Machine
6	HG2	Lever arm connection	direct lever arm connection	-1.622,72	MC/Machine
7	HG2	Optics	change grip caps material to ABS	[redacted]	MC/Machine
8	HG2	Optics	change grip rings material to ABS	[redacted]	MC/Machine
9	HG2	Cushion	change coating material to artificial leather	-122,13	MC/Machine
12	HG3	Tray	tray from milonizer	-65,51	MC/Machine
13	HG3	HMI	no pulse receiver	[redacted]	MC/Machine

Figure A.45: Cost estimate for the concepts of the Chest Press[125]

Cost estimate Seated Rowing concepts

Q Seated Rowing					
Measure	Grade	Component	Change with respect to Q	Potential	Unit
1	HG1	Side mounting	welded rectangular profile with PA66 cover, without inlay cover, no lifting column	-5.642,83	MC/Machine
2	HG1	Optics: Side mounting, seat structure, lever arm	change powder coating material to tiger drylac RAL9005	-144,34	MC/Machine
3	HG1	Casing	casing material standard ABS without PMMA foil	[redacted]	MC/Machine
4	HG1	Display holder	display connection rectangular profile without casing	none	MC/Machine
5	HG1	Lever arm	two bent grips	333,09	MC/Machine
6	HG2	Lever arm connection	direct lever arm connection	-1.622,72	MC/Machine
7	HG2	Optics	change grip caps material to ABS	[redacted]	MC/Machine
8	HG2	Optics	change grip rings material to ABS	[redacted]	MC/Machine
9	HG2	Cushion	change coating material to artificial leather	-111,03	MC/Machine
12	HG3	Tray	tray from milonizer	-65,51	MC/Machine
13	HG3	HMI	no pulse receiver	[redacted]	MC/Machine

Figure A.46: Cost estimate for the concepts of the Seated Rowing[126]

125 created with Microsoft Excel as of 12th June 2019
126 created with Microsoft Excel as of 12th June 2019

Cost estimate Abdominal Crunch concepts

Q Abdominal Crunch

Measure	Grade	Component	Change with respect to Q	Potential	Unit
1	HG1	Side mounting, seat structure	welded rectangular profile with PA66 cover, without inlay cover	-3.119,65	MC/Machine
2	HG1	Optics: Side mounting, set structure, lever arm	change powder coating material to tiger drylac RAL9005	-144,34	MC/Machine
3	HG1	Casing	casing material standard ABS without PMMA foil	[redacted]	MC/Machine
4	HG1	Display holder	display connection rectangular profile without casing	none	MC/Machine
7	HG2	Optics	change grip caps material to ABS	[redacted]	MC/Machine
8	HG2	Optics	change grip rings material to ABS	[redacted]	MC/Machine
9	HG2	Cushion	change coating material to artificial leather	-111,03	MC/Machine
12	HG3	Tray	tray from milonizer	-65,51	MC/Machine
13	HG3	HMI	no pulse receiver	[redacted]	MC/Machine

Figure A.47: Cost estimate for the concepts of the Abdominal Crunch[127]

Cost estimate Back Extension concepts

Q Back Extension

Measure	Grade	Component	Change with respect to Q	Potential	Unit
1	HG1	Side mounting	welded rectangular profile with PA66 cover, without inlay cover	-3.119,65	MC/Machine
2	HG1	Optics: Side mounting, set structure, lever arm	change powder coating material to tiger drylac RAL9005	-144,34	MC/Machine
3	HG1	Casing	casing material standard ABS without PMMA foil	[redacted]	MC/Machine
4	HG1	Display holder	display connection rectangular profile without casing	none	MC/Machine
5	HG1	Lever arm	no auxiliary drive, locking bolt and disc	-980,96	MC/Machine
7	HG3	Optik	change grip caps material to ABS	[redacted]	MC/Machine
9	HG2	Cushion	change coating material to artificial leather	-166,55	MC/Machine
10	HG3	Cushion	round cushion lever arm	-63,95	MC/Machine
11	HG3	Power unit	change to bevel geared motor from batch 3	[redacted]	MC/Machine
12	HG3	Tray	tray from milonizer	-65,51	MC/Machine
13	HG3	HMI	no pulse receiver	[redacted]	MC/Machine

Figure A.48: Cost estimate for the concepts of the Back Extension[128]

[127] created with Microsoft Excel as of 12th June 2019
[128] created with Microsoft Excel as of 12th June 2019