The Flexibility Trainer: Feasibility Analysis, Prototype- and Test Station Development for a Sports Device for Hip-joint Flexibility and Strength Enhancement

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Abstract: Martial Arts, dancing, and gymnastics are among the sports that depend on outstanding hip-joint flexibility and strength to successfully perform high level techniques. Latest research suggests that flexibility and antagonistic strength are strongly related and require agonistic strength training. Therefore, the aim of the study was to develop a model prototype of a device that utilises flexibility-enhancement reflexes and provides appropriate means for strength training and delivers hip joint range-of-motion (ROM) increase. The device provisionally called Flexibility Trainer (FT) is equipped with sensors that measures and estimate the athletes' hip joint moments during training. The FT aims to utilise the athletes body weight while performing controlled leg spreads. Its main components are a rail system with 2 slides and foot mounts (tiltable and turnable), a hydraulic braking system for force independent constant velocity slide (nearly isokinetic), a force sensor and a holding device. It is hypothesised that the leg-spread movement activates the reciprocal-inhibition reflex and increases antagonistic strength, whereas the leg-closing movement activates the autogenic-inhibition reflex and leads to serial hypertrophy. A model for hip-joint moment calculation based on force sensor and motion capturing data is proposed.

1 INTRODUCTION

Hip-joint flexibility (HJF) and strength are essential pre-requisites for most sports, but particularly Martial Arts, dancing and gymnastics that are highly dependent on it (Hölbling, Preuschl, Hassmann, & Baca, 2017; Shan, 2005; Weber, Bedi, Tibor, Zaltz, & Larson, 2015).

Training this ability can be challenging, as the improvement of the range-of-motion (ROM) involves physiological and neuronal adaptations (Alter, 2004; Moreira & Gonzaga, 2012) and it decreases with age and periods of immobility (Roaas & Andersson, 1982). However, recent research suggests different physiological and neuronal methodical approaches result in measurable short- and long-term adaptions of active and passive hip-joint flexibility.

1.1 Methodical Approaches for Short-term Adaptions of ROM

Most short-term approaches are based on neuronal adaptions, such as decreased residual muscle tone and increased stress tolerance (Sharman, Cresswell, & Riek, 2006). Current publications have outlined the benefits of reciprocal and autogenic inhibition activation (Rowlands, Marginson, & Lee, 2003).

1.1.1 Reciprocal Inhibition

Reciprocal inhibition is "a process that inhibits the stretch reflex in antagonistic pairs of muscles. When

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one muscle contracts it sends inhibitory nerve impulses to its opposing muscle causing it to relax" (Kent, 2006, p. 458). Therefore, the reflex can be used inversely to increase the flexibility in one muscle, by contracting its antagonist.

1.1.2 Autogenic Inhibition

Autogenic inhibition (or inverse myotatic reflex) describes a "reflex inhibition of a motor unit in response to excessive tension in the muscle fibres it supplies" (Kent, 2006, p. 62). The reflex results in increased ROM after contraction of the limiting muscles.

1.1.3 CRAC- PNF Training

Proprioceptive neuromuscular facilitation (PNF) training describes "an effective stretching technique for increasing the joint's range of motion. All PNF procedures require a partner and involve a pattern of alternating muscles' contraction and relaxation while stretched. In this way the Golgi tendon organs are stimulated (Kent, 2006, p. 441). A particular promising variant called Contract-relax-agonist-contract (CRAC) combines a contraction of the targeted (stretching) muscle (TM), followed by relaxation and contraction of the opposing muscle (OM) to reach a wider position culminating in additional passive stretch (Sharman et al., 2006). This method is believed to activate both, reciprocal and autogenic inhibition, which results in a significantly higher ROM increase, compared to traditional flexibility training methods. Sharman et al. (2006). report a gain of 3-9° in joint angle by this method, which would theoretically result in 6-18° for full leg spreading.

1.2 Methodical Approaches for Long-term Adaptions of ROM

Long-term enhancements in flexibility are normally accompanied by physiological adaptions. Thereby, active ROM is strongly dependent on OM (agonist of the spreading movement) strength, whereas passive flexibility is primarily related to the stretching muscle's length and elasticity. Recent research reported that full-ROM strength training (if performed in both opposing movement directions) leads to both increase of OM strength and serial hypertrophy (particularly eccentric motions) of the TM (Csapo, Alegre, & Baron, 2011; Franchi et al., 2014).

1.2.1 Agonistic Strength

The agonistic muscle (OM) strength constitutes a key factor to significantly enhance active flexibility, especially in fast sports movements opposing the gravitational pull. Increase in maximum strength can be achieved by intramuscular strength (IC) or (parallel) hypertrophy training (HT). This requires 1 to 3 repetitions at 90-100% of one repetition maximum (1rpm) resistance for IC or 8-12 with 60-80% of 1rpm for HT, varying between authors.

1.2.2 Serial Hypertrophy of TM

Recent research states that full-ROM strength training, particulalry (but not solely) in eccentric motion leads to increased muscle length, due to additional serial muscle fibre sarcomere production (Csapo et al., 2011; Franchi et al., 2014).

1.3 Isokinetic Training

To enable a sport device to allow for different number of repetitions and percentages of 1 rpm and to simultaneously decrease the injury propability, an isokinetic mode is believed to be advantageous. Isokinetics in general describes "exercise with an accommodating resistance and a fixed speed" (Brown, 2000, p. 6).

1.4 Device Development

The aim of the study is (a) to design a device which combines static and dynamic CRAC-PNF with full-ROM strength training in an isokinetic training mode for an increase of hip joint flexibility in side (abduction/ adduction) and front split (flexion/ extension) direction, (b) to investigate its' feasibility (c) to manufacture a simplified prototype and (d) to propose an appropriate participant specific test setup.

2 MATERIALS AND METHODS

The design process was structured in four main phases *product planning*, *conception*, *product design* and *detailing for production* according to Pahl and Beitz (2013) and VDI2221 (2019). The first 2 phases are considered as pre-analysis phases and can therefore be found in the methods section, whereas later include detailed calculations, which can be found in the results and discussion section.

Planning Phase: A requirement list was developed to address customers' needs as outlined in Hölbling (2016) and illustrated in Table 1.

Table 1: Requirement list. The list covers customer needs and patent specification from Hölbling (2016). Table column 2 distinguishes between fixed requirements (F) and wanted requests (W).

Function	F/W	Description
Sliding system	F	Linear movement direction
Sliding system	F	Coupled motion for symmetric exercises
Sliding system	W	Foldable for easy transportation
Feet fixations	F	Fixation of feet on sliders rotatable around 360°
Feet fixations	F	Foot fixations must be tiltable >40° to avoid ankle injuries
Damping system	F	Damper to slow down foot rotation in the foot ankle joint
Brake system	F	Movement with adjustable velocity from 0,1 m/s to 0,3 m/s, at design load of maximum expected load.
Frame	W	Minimized weight for easy transportation
Handle	F	Adjustable in height
Force Sensor	W	Measure the combined leg spreading and closing force, withstanding maximum loads.

Conception Phase: To achieve the main functions, the product was segmented into functional modules: *rail system*, *sliders*, *braking system*, *holding device* and *force sensors*.

The *design phase* includes detailed descriptions of the main device components of a first market-ready version, including stress analysis, due to the external loads during usage. Therefore, this section covers *aim a-b*.

In the *detailing phase* some changes of the device design are proposed, to address *aim c*.

A setup for device testing and analysis of general and sport specific flexibility is proposed as stated in aim d).

3 RESULTS AND DISCUSSION

3.1 General Components

The outlined design consists of two sliding mechanisms (1), running on U-Profiles (2) with rotating foot straps (3), shown in Figure 1. The foot straps can be set by locking pin at every 90°. The sliders are connected with a circulating steel cable (4) guide rollers are located at the outer end (5) of the U-Profiles to ensure symmetric motion. The damper unit of the braking system (6) is placed inside the U-Profile. The trainer can be folded at the connection plate (7) for easy transportation. The handles (8) are height adjustable by lock pins (9) and are mounted in injection moulded foldable plates (10).

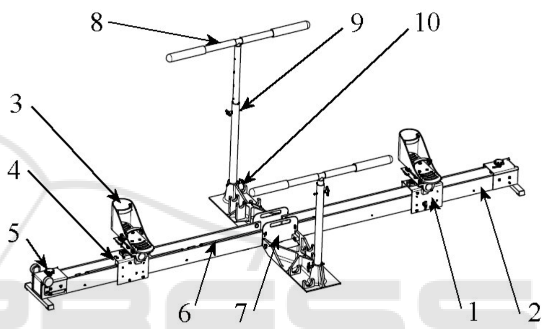

Figure 1: Design of Flexibility trainer.

3.2 Calculations of External Loads

The expected user generated maximum loads are calculated using maximum hip moment and the user's weight (see Figure 2).

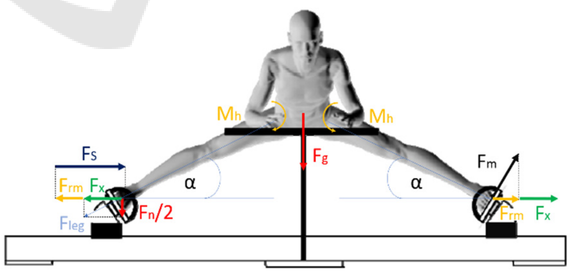

Figure 2: Illustration of the force calculation method in abduction [4].

[4] Legend:
F_g = Gravitational force
F_n = Normal component of gravitational force
F_x = Horizontal component of gravitational force
F_{rm} = Horizontal component of muscular force
F_S = Spreading force
M_h = Cumulated moment of hip joint
g = Gravitational acceleration
α = angle leg axis to floor
l_{leg} = leg length
h_{eff} = effective component of leg length

For the calculation of F_{rm}, the possible M_h from an Isokinetic test is approximately linearized (based on the isokinetic hip abduction and adduction test of a highly skilled Martial Artist, shown in Appendix A and divided by effective height.

$$F_{rm} = \frac{M_h}{h_{eff}} = \frac{150\,Nm - 1.35\frac{Nm}{°}*(90° - \alpha)}{l_{leg}*\sin(\alpha)} \quad (1)$$

The component F_x of bodyweight F_g is

$$F_x = \frac{F_g}{2*\tan(\alpha)} \quad (2)$$

The resulting maximal force on the slider is the sum of F_{rm} and F_x equal to approx. 2200 N at the minimal possible α of 15°. Leg length is assumed 1 m and the body weight up to 110 kg (see Figure 3).

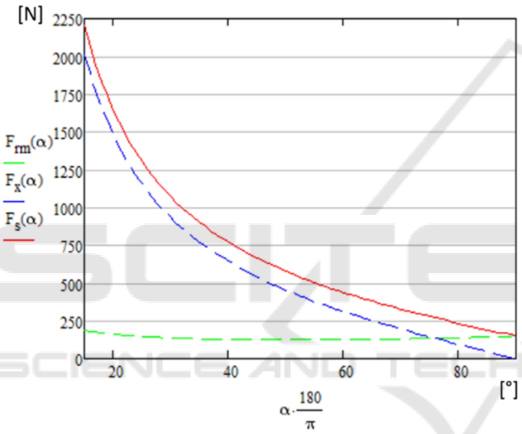

Figure 3: Horizontal forces on slider depending on α.

This is also the assumed load for the braking system and the other slider components. The selected damper should work for speed up to 0.3 m/s at this load.
The force sensors should have a range from 100 N to 5000 N in pulling and pushing directions.

3.3 Components and Specific Loads

3.3.1 Rail System

The main part of the rail systems are the U-Profiles 100x80x10 mm. For weight reduction purpose the chosen material is *Polyamid*. Maximal stress and deformation is obtained via *FEA* (*Finite Elements Analysis;* (Klein, 2012)*)*. Maximum stress level of 25 MPa is located around the mounting holes as expected and is well below the critical stress level (Figure 4). The detailed model description is available in Stummer (2016)

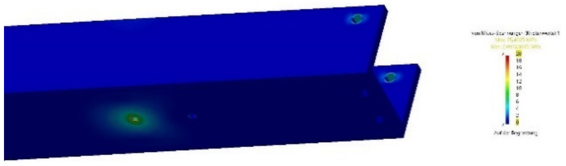

Figure 4: *Von Mises* stress on polyamid U-Profile (Stummer, 2016).

Inside the rail track two adjustable hydraulic brake cylinders *HB-40-500* and *HB-40-600* (6) from supplier *ACE* (Figure 5) are placed in series. The maximum allowed force is 4000 N for the longer 600 mm cylinder.

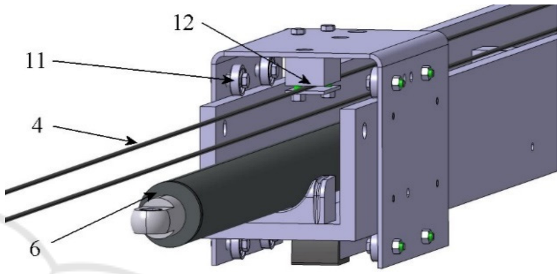

Figure 5: Rail and slider system of one side.

The sliders are running on the U-Profile with *SKF 635 ball bearings* (11) to minimize the friction. Both sliders are clamped to the steel cable (4) by sheet metal (12) and *M5 screws*. For cable turn at the end of the U-Profile *guide pulleys 10/3* (13) from *Ingo Quirnbach Industrieservice* are applied (Figure 6). The two upstanding *rollers 20K JGV 050-2* (14) from *Dematech* are for transportation issues.

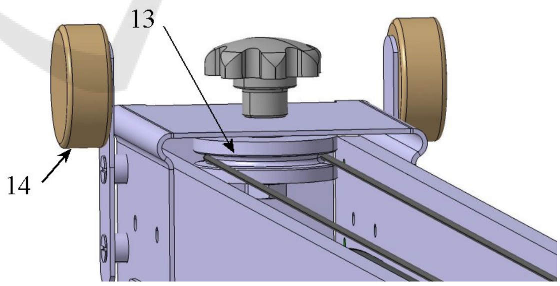

Figure 6: Rollers at the outer end of the U-Profile.

3.3.2 Sliders

The main frame of the slider is profiled from a metal sheet of 3 mm thickness and connected to the braking system by a detachable lock pin (15) as shown in Figure 7. This enables dismantling for folding and transportation.

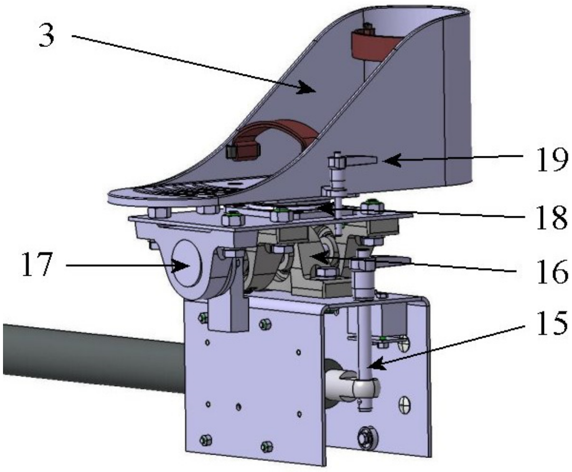

Figure 7: Slider with ankle tilt system and foot mount.

The ankle tilt mechanism, consisting of roller bearings with housing *SY 12 TF* from *SKF* (16) and *rotational damper WRD-H-3015-C* from *Weforma* (17), is mounted on the slider frame. The torque of the selected damper is adjustable from 2 to 14 Nm and should reduce unintended ankle wobble.

A turntable (18) is placed between the foot mount and the ankle tilt mechanism to allow the foot mount rotation of 360° for spread training lateral and longitudinal. It can be fixed every 90° by the lock pin (19).

The foot mount (3) is manufactured by *FDM (Fused Deposition Modelling)* for the prototype. For serial production it will be injection moulded.

3.3.3 Holding Device

The choice of material for the tubes (8), of this essential safety feature as shown in Figure 8, is *CFRP* (carbon fibre reinforced plastic). Pre-ordered tubes can be glued together with aluminium T-piece (20) to form the handlebar. For ergonomic reasons, the handlebar is height adjustable and fixed by a lock pin (9).

The connection plate (10) is an injection moulded part. The maximum stress is calculated at a horizontal force of 300 N on the handlebar that leads to a bending moment of 270 Nm at the tube mounting dome. The *FEM* results show a maximum stress of 42 MPa at a single node (see Figure 9 and Stummer (2016) for more details).

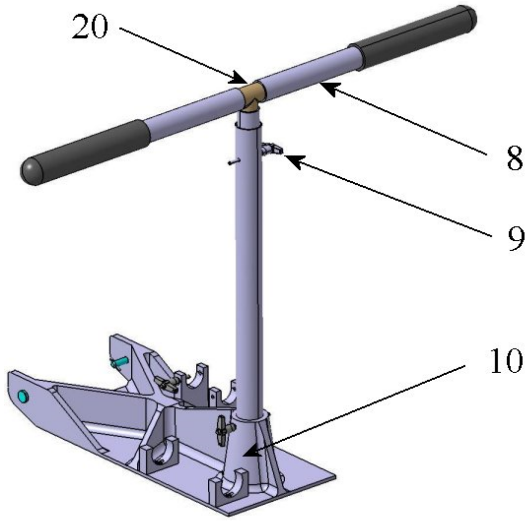

Figure 8: Handlebar of *CFRP tubes*.

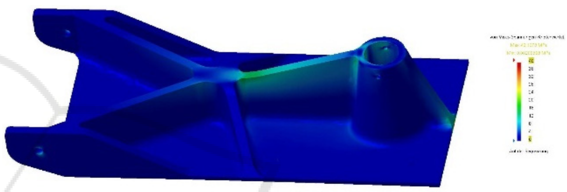

Figure 9: *Von Mises* stress on connection plate (Stummer, 2016).

The maximum stress in the ribs is less than 20 MPa i.e. safely below critical stress.

3.3.4 Force Sensor

As stated in section 0, the expected maximum force at the sensor is about 2200N per leg. Therefore, the sensor should have a measuring range from 100N-5000N. A *U9c force sensor* for forces up to 20kN has been identified.

3.4 Changes for the Prototype

Due to manufacturing reasons some parts of the design needed to be changed from the planned serial manufacturing to prototyping (see Figure 10):

- Due to high costs, the injection moulded mounting plates were changed to aluminium plates.
- The minimum length of Polyamid U-Profile was changed to aluminium profile.

- As a consequence of the rail profile change the sliders are now running on linear guide inside the profile instead of the roller bearings outside.
- The foot mount changed from a 3D printed part to mini skates available on the market.
- The holding devices are made of steel.

Figure 10: Manufactured prototype.

3.5 Proposed Test Setup

In order to comprehensively test the device and its short-term effect on athletes, a testing setup utilizing a *Vicon® motion capturing system* and a force sensor within the device for measuring the force alongside the rail, is proposed. The setup is specifically designed to provide a detailed estimation of the hip joint moments, to evaluate the athletes' physical strain during exercising in order to make propose future training adaptations. In addition, the setup includes a stage for practical measurements, such as static flexibility tests and sport specific movements, as well as a stage for device training.

3.5.1 System Setup

As stated above, the setup comprises both, one sport-specific (e.g. Martial Arts) and one device-specific movement analysis volume. The combined volume is surrounded by 12 high-resolution infrared cameras, specifically aimed to capture all markers, which are attached to the athlete during the exercises, see Figure 11.

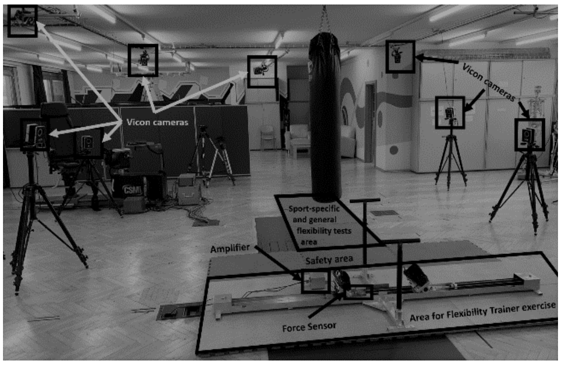

Figure 11: Proposed test setup for sport-specific and general flexibility tests.

3.5.2 Hip-joint Moment Calculation

To calculate the hip joint moment with inclusion of the external forces of the flexibility trainer, a kinematic model of the hip joint centre, based on a marker model and anthropometric data is required. The Vicon® plug-in-gait model is applied (Vicon®, 2016). Hip joint angles can be obtained using the *static and dynamic* plug-in-gait modelling function. Centres of rotation are calculated by the *functional skeleton calibration*.

Based on Figure 2, the cumulative hip moment (for leg spreading) can be estimated by following inverse calculation retrieved from the linear sensor force and reduced by the gravity component[5]:

$$M_h = \frac{F_S - {}^1/_2 \times F_g \times \cos(\propto)}{\cos(90-\propto)} \times l_{leg} \qquad (3)$$

The cumulated hip-joint moment M_h can then be divided into the 3 movement direction components[6] (M_x, M_y, M_z) by splitting it in relation to the calculated components from Vicon® (M_{Vx}, M_{Vy}, M_{Vz}), as the kinematic parameters, such as movement directions are the same with and without resistance.

$$M_x = \frac{M_h}{M_{Vx}+M_{Vy}+M_{Vz}} \times M_{Vx} \qquad (4)$$

$$M_y = \frac{M_h}{M_{Vx}+M_{Vy}+M_{Vz}} \times M_{Vy} \qquad (5)$$

$$M_z = \frac{M_h}{M_{Vx}+M_{Vy}+M_{Vz}} \times M_{Vz} \qquad (6)$$

[5] For Legend, see Figure 2
[6] Legend:
M_x = Hip flexion moment
M_y = Hip abduction moment
M_z = Hip rotation moment
M_{Vx} = Vicon® calculated hip flexion moment
M_{Vy} = Vicon® calculated hip abduction moment
M_{Vz} = Vicon® calculated hip rotation moment

3.6 Summary of Outcomes

The proposed final construction fulfils additional framework conditions, such as weight and design specifications, which will be necessary for a commercially viable product, but are too expensive for a prototype. Therefore, the design was optimized in order to provide more safety and stability for significantly lower costs. The testing setup is opted to provide analysis possibilities for sport-specific and general flexibility tests, as well as for the device training analysis. Furthermore, to comprehensively analyse the physical strain during the training, a mathematical model for joint moment analysis was used, based on the Vicon® model and the force sensor data.

3.7 Limitations

The calculation model does currently solely comprise the leg spreading motion because at the leg closing motion the participant is estimated to reduce the gravitational force by supporting his body weight on the holding device. Therefore, to analyse the closing moment, an additional sensor measuring Fg would be needed, or the result would be given as a function from 0-100% of body weight reduction. Furthermore, marker position changes due to skin shifts might add large error to the results of the separated moments. Usability and effect sizes are not available yet.

4 CONCLUSIONS

The Flexibility Trainer prototype is expected to have the potential to enhance the training of active and passive flexibility, even more than with CRAC-PNF methods, due to cumulated effects of combined methodical approaches (isokinetic, full-ROM strength training with CRAC), which might also last longer. Furthermore, based on the tests and component data sheets, the device should resist all expected loads without damages and meet the requirements. However, future studies are needed to proof short- and long-term functionality.

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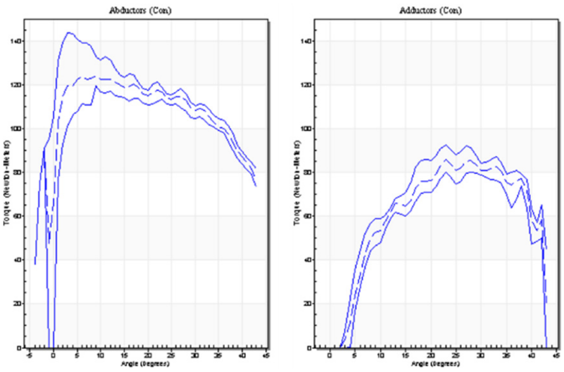
APPENDIX



Appendix A: Isokinetic hip joint adduction and abduction tests of a highly skilled Martial Artist with a height of 1.82m and a weight of 78kg on a Humac® CSMI device.